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INVESTIGATION OF METHODS OF RAILWAY TRAIN LIGHTING

BY

EDWARD WRAY

A THESIS SUBMITTED FOR THE DEGREE OF ELECTRICAL ENGINEER
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FOREWORD

In presenting the report of this investigation the writer realizes that it deals with the operation of commercial apparatus manufactured and installed by private interests, and accordingly a determined effort has been made to eliminate all commercialism, presenting merely the facts as they were found in the pursuit of the tests of this apparatus.

The work has been done in connection with the college of engineering of the University of Wisconsin by parties aggregating ten engineering students with which the writer was associated. The details of these tests may be obtained from the graduating theses written by the senior students of these parties, to which due reference is made later. This report contains no minor data, in that only the typical results, as selected from the great mass of test data, are presented.

I wish to take this occasion to express my appreciation of the interest and efforts of the various railway officials under whom this series of tests has been carried out, without which it would have been impossible. I refer to Mr. C. B. Young, Mechanical Engineer, C. B. & Q. Ry., Mr. W. J. Bohan, 'Chief Draughtsman, Northern Pacific Ry., Mr. J. F. De Voy, Mechanical Engineer, C., M. & St. P. Ry., Mr. A. J. Farrelly, Electrical Engineer, C. & N. W. Ry.

Mr. F. W. Huels, instructor in steam engineering, University of Wisconsin, very ably conducted the tests of the Westinghouse Engine equipments on the C., M. & St. P. Ry., and the C. & N. W. Ry., and is now following this with some tests to determine the effect of reciprocating engines and turbine equipments in the baggage car, on train vibration.

I also wish to thank the senior students of the testing crews for their efforts and assistance in making these tests: I refer to Messrs. W. A. Bertke, J. I. Bush, O. B. Cade, H. L. Heller, A. U. Hoefer, Edgar Kearney, C. S. Peters, I. L. Reynolds and A. J. Walsh.

I also wish to take this occasion to express my deepest appreciation of the able guidance and inspiration given to this investigation by my friend and teacher, D. C. Jackson, Professor of Electrical Engineering, University of Wisconsin.

EDWARD WRAY.

INVESTIGATION OF METHODS OF RAILWAY TRAIN LIGHTING

CHAPTER I

INTRODUCTION

The subject of railway car lighting is one which, like the railway itself, has developed with the times. It is a tradition that the honor of first lighting railway cars belongs to one Thos. Dixon, the driver of the *Experiment,* as the coach was called, on the Stockton & Darlington Railway, England, in 1825. It is said that on the dark winter nights, out of pure goodness of heart, he used to bring in a penny candle and set it on the rough oak board that served as a table in the center of the coach. In those days the railway companies made no effort to light their cars except to offer candles for sale to passengers. Gradually times changed and the railway companies furnished a few smoky candles to be placed in each car. This was only to enable the passenger to find his way in and out of the car and took no thought of his real comfort and accommodation. Later, oil lamps were substituted in place of the candles, and these, though at first only a slight improvement over candles, were improved and developed to give a fairly good light as the railway practice developed.

Car lighting has followed the same general lines of development as have the common methods of house and street illumination, but at no time till within the last few years has any method of railway car lighting been equal to that employed in houses or public places. The reason for this is obviously in the great difficulty of adapting any method of illumination to the severe conditions of railway service. But, nevertheless, practically all of the house and street illuminants have been utilized in lighting railway trains and in addition to this the vast application of compressed Pintsch gas for lighting railway cars has been developed.

While a consideration of all of the various methods of car illumination would be very interesting, they cannot be considered within the limits of this investigation, so in the ensuing chapters the subject will be treated only in the application of electricity to the illumination of railway cars.

As early as 1881, the London, Brighton and South Coast Railway of England tried lighting some of their cars from electric storage battery sets, and at the same time experimented on trains with dynamos, located in the guards' van, driven from the car axle. This, by the way, was only two years after the development of the incandescent lamp.

Several experiments on other English railways followed directly; the Great Northern equipped several trains with a dynamo mounted in the guards' van driven by the car axle and furnishing light to the entire train, there being a storage battery auxiliary to light the lights while the train stopped. A little later, the Great Eastern equipped eighteen trains with a system employing a dynamo located on the tender driven by a steam engine; this receiving steam from the locomotive. On these trains an auxiliary storage battery was placed on each car.

The results of these early experiments in England seemed to favor the axle driven system as operated on the Brighton; that company being so well satisfied with the equipment as to operate about 300 cars by this method of lighting, and the company still operates about 200 cars on the same principles. These, however, are being rapidly replaced by the Stone axle equipment, described more fully later.

In France, as early as 1886, a train was equipped with a set of bi-chromate primary batteries and was operated for a year or so on cars running between Paris and Brussels. Numerous experiments were also made using lead accumulators to light the cars, but these, due to the imperfect and expensive lead accumulators of that day, were quite inconclusive and unsatisfactory.

Later, however, as the lead cell was perfected and cheapened in price, this type of equipment came into more general use in France.

In Germany the use of storage batteries was developed at an early date to such an extent that by 1893 about 2,500 mail cars alone were equipped with this form of illumination.

In 1898 the Prussian State Railways conducted a series of tests on the Stone axle equipment (see page 12) but after about two years' trial of these equipments they were abandoned and all apparatus was removed from the cars.

Later, in 1900, the Prussian State Railways began experimenting with steam driven generators, and as a result of these experiments have adopted as standard equipment, a system using a steam turbine generator set located on top of the locomotive that operates at full boiler pressure and is controlled by the engine driver. There is also an auxiliary of storage batteries on the cars for use during engine changes. This equipment is very satisfactory and its operators believe they have at last found a solution of the train lighting problem.

Developments in America did not receive such a stimulus in the early days. In 1886 the Boston and Albany Railway equipped a few cars with straight storage battery equipments as an experiment, but found it rather expensive as shown by the statement of Mr. F. D. Adams, their Master Car Builder, in 1892 when he said "no road can afford to put electric lights on its trains; any road of modest dimensions would be ruined by it in a little while." In the year 1885 the Pennsylvania Railroad Company equipped eight of its parlor cars with storage cells for lighting purposes. The next year witnessed an active campaign by the two battery companies then in existence and several cars were equipped with this type of equipment and to this day the Pennsylvania road has a large percentage of cars equipped with straight storage battery lighting.

The Chicago, Milwaukee and St. Paul Railroad has been particularly active in the development of the steam driven generator sets, more commonly known as "baggage car" or "head-end" sets. As early as 1888 this road equipped a special car with a boiler and engine-generator set, the purpose of which was to furnish both light and heat to the whole train during the winter months. In the summer the engine and dynamo were transferred to a baggage car where they operated to light the train. This equipment was successful in its operation and gave some gratifying results in regard to cost of operation. These are discussed more in detail in another part of the report and will not be considered further here. Sufficient to say that that road has adopted the high speed Westinghouse engine-generator set located in the baggage car, as standard equipment, and is at present using essentially the same equipment, having about 300 cars equipped for this kind of lighting.

Recently the General Electric Company has developed a Curtis turbo-generator set for this service operating at 3,600 R. P. M., which is also discussed at length later and will only be mentioned here.

The De Laval Turbine Company have several turbo-generator sets in operation on the Pennsylvania Railroad for lighting its through trains. These are located in the baggage cars and operate at 20,000 R. P. M., a 10 to 1 gear transmission driving the generator at 2,000 R. P. M.

The Pennsylvania Railroad Company has also recently equipped several of its engines with Curtis turbine generator sets located on top of the locomotive such as the Germans have found so satisfactory.

The development of the more modern methods of axle lighting has been worked out largely in America, and some of the more typical devices will now be described. The axle lighting problem is, however, discussed more comprehensively on page 111.

DEVELOPMENT OF AXLE LIGHTING IN ENGLAND

The earliest attempt at lighting a train by means of a generator driven from the axle was probably that made in 1883 by the London, Brighton and South Coast Railway in England. A generator was mounted in the guard's van and was belted to the axle. A mechanical device served both as pole changer and automatic switch. This consisted of a large threaded screw or worm fitted into a half cylinder laid horizontally. Mercury was then poured in and the worm belted to the generator. As the speed increased the mercury was forced to an end of the cylinder and completed the field circuit of the generator. There were two pairs of armature brushes, one pair only operating at once. These were mounted on a rocker frame which, when the circuit was closed in one tube, was caused to swing over by an electro-magnet so as to engage the proper brushes with the revolving armature. On reverse direction the mercury was forced into the other end of the tube by the revolving screw and the other pair of brushes made to operate. thus keeping the proper polarity in the circuit. No provision is mentioned for regulating voltage. the battery being depended on as a regulator. When the lights were on and the generator furnished too much current the battery took the excess and when not furnishing enough the battery made up the deficiency. When the speed of the train slackened the fall of mercury in the tube broke the circuit.

This equipment seemed to give satisfactory results. which is surprising in that no attempt was made at voltage regulation, but this is undoubtedly explained by the fact that they used a large battery. 500 ampere hour, with a 56 ampere 40 volt machine. so that on the higher speeds the increased battery charge would cause greater armature reactions. which were undoubtedly high in that machine. and would so tend to regulate the voltage inherently. This in the present stage of development would be considered as deplorably poor and unsatisfactory. though in the early days it satisfied the operators.

Later, on this same line. a modification of the above was employed in that regulation of the generator voltage was attempted by shifting the position of the brushes as the train speed increased. thus decreasing the effective coils in the armature winding. This was effected by means of a centrifugal governor which also served to close the generator circuit when the critical speed was reached. In this equipment which was very extensively employed on that road at the time. the generator and regulator were located on the guard's van and supplied light to the whole train of ten cars.

Later. in about 1896. a system known as the Stone system was developed and will now be considered.

THE STONE SYSTEM OF AXLE LIGHTING

This equipment was invented in 1895 by Mr. A. B. Gill, and was developed and improved by Messrs. J. Stone & Co., of Deptford, England, hence is known as the Stone system. It has reached almost universal adoption on the English railways and accordingly a consideration of the equipment must be accorded in this investigation.

The characteristic feature of the equipment is that each car is a unit by itself, thus affording a much more flexible system than that of the earlier systems of England, where the generator was located in the guard's van, this being suitable for block trains only. The equipment consists essentially of a generator, a storage battery to act as auxiliary when the generator is inoperative, and an automatic switch to close the generator circuit when the critical speed has been attained.

The principle underlying the operation of this equipment is that regulation is obtained by allowing the belt to slip. As the speed of the train rises the generator voltage will tend to rise proportionally, this causing a great battery charging current to flow, thus increasing the generator output and belt pull.

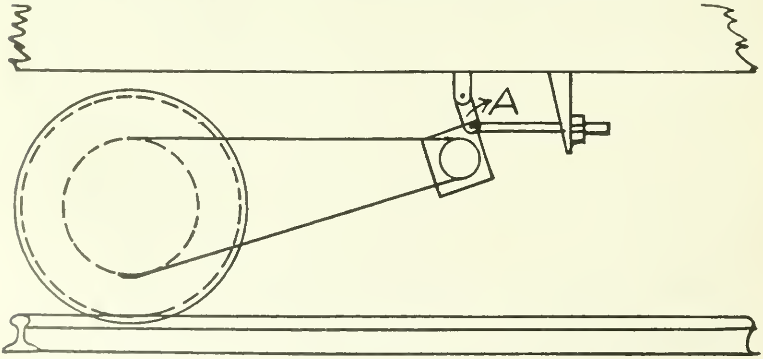

PLATE I.—SHOWING PLAN OF GENERATOR SUSPENSION.

The generator suspension is shown on Plate I. It is supported at one corner of its frame by the adjustable link A, in such a manner that it is free to swing toward or away from the driving axle. The suspending link is so placed that the belt draws the dynamo out of the diagonal position in which it would naturally hang, thus putting a definite tension on the belt, just sufficient to absorb the power required. It is obvious that when the pull on the belt exceeds that due to the offset suspension of the dynamo that the dynamo will be drawn toward the axle and the belt allowed to slip. Thus the generator will run at practically constant speed for all values of train speed above the critical value.

A strong mechanical governor automatically closes the generator circuit when critical speed has been reached.

A storage battery is suspended underneath the car to act as auxiliary in lighting the lights when the generator is inoperative. Another function of the storage battery is that it acts as a ballast or regulator to keep the lights constant, absorbing all the variations of generator output.

The lubrication of the generator is effected by means of an electrically controlled oil supply so adjusted that when the generator is operative oil will flow from the oil tank, but when the generator is inoperative the supply is cut off and no waste takes place.

The operation of this equipment is shown by the accompanying data of a reported test made in the presence of Professor Slaby, director of the Berlin Royal Technical College, and Professors Hagen and Neesen of the German Patent Office.

Train speed.	Speed of Dynamo.	Equivalent speed if no slipping had occurred.	Output Amperes.	Reference.
12	500	500	0	Ry. Gaz., 1898, 668.
16	690	690	2	
18	750	750	6	
20	840	840	14	
22	885	925	17	
24	915	1.025	20	
27	915	1.125	20	
30	915	1.250	20	
45	915	1.875	20	
48	915	2.000	20	
54	915	2.250	20	
60	915	2.500	20	
72	915	3.000	20	

The pre-determined speed of dynamo was 915, at which it should deliver 20 amperes. It should be noted that this was not exceeded.

In regard to the power absorbed, a test made by Professor Capper of Kings College, London, is quoted. For ordinary coaches when running at normal speeds it was found to require 0.6 H. P. to drive the generator while lighting the lights. For speeds of the express train the power absorbed does not exceed 1.1 H. P. No data are given in regard to K. W. output of generator nor exact values of speed.

The extensive use of this equipment in England is shown by the fact that by 1902 the London and Northwestern Railway had 4,000 carriages equipped with this system of lighting; also the London, Brighton and South Coast Railway had, in 1902, 293 coaches equipped with this same system. At present, in 1906, the Great Central has 330 coaches equipped, according to information given to the writer by Mr. N. Clow, Assistant Superintendent of the Line, Great Central Railway, England.

Further in regard to lamp regulation this official reported that when properly regulated, the rise and fall of voltage is not perceptible. An idea of voltage regulation may also be gained from the fact that he reports that during a period of four months operation only five lamps were burned out. This would indicate that the lamp voltage at least did not rise much above normal, but is no criterion for the lower limit which is really the important one.

In discussion of this equipment it may be said that it has the advantage of extreme simplicity and cheapness of construction in comparison with some of our later American devices. However, from a standpoint of reliability and regulation, the advantage would seem to be with the more modern American devices. The test quoted is one made in a laboratory under ideal conditions and is not typical of operations under varying weather conditions of ice and snow and rain in addition to the collection of cinders, dust and stones from the track at high speeds, while the tests quoted later of some of the American devices were made while in actual operation on the trains under unfavorable weather conditions.

Another English road having 4,000 cars equipped with this system reports that: "The light is good and steady whether standing or running and no difficulty has been experienced during winter from frost or snow."

This type of equipment has been used more or less extensively in this country under the name of the Gould system. It was, however, quickly displaced by the more modern equipments employing electrical means of regulation, which would seem to indicate that, from the American standpoint at least, the Stone system is inferior to some of the more modern equipments.

In regard to the power absorbed, attention must be called to the fact that at normal speeds it requires 0.6 H. P. to light the car, but for express speeds it requires 1.1 H. P. to furnish lights, as per test quoted above.

This would indicate a tremendous belt loss at the higher speeds which is just as would be expected. If all the slip takes place on the armature pulley, which undoubtedly is approximately true, the power required to drive the generator would vary directly as the train speed, for, the tension of the belt being assumed constant, the power delivered by the axle would be directly proportional to the product of this tension and axle speed. This is certainly a disadvantage of the system in that it causes a useless drag on the locomotive at high speeds and will also result in the rapid destruction of belts.

CHAPTER II

DESCRIPTION AND DISCUSSION OF SEVERAL METHODS OF LIGHTING RAILWAY CARS FROM THE CAR AXLE

MOSKOWITZ SYSTEM

Of the earlier American devices for axle lighting, one of those developed by Morris Moskowitz in 1895, is most worthy of note. Mr. Moskowitz has been especially active in the development of axle devices, having developed numerous types, this one being one of his earliest. It consisted essentially of a generator with its driving gear, two sets of storage batteries, a switchboard and lamp circuit in the car and an automatic switch to close the generator circuit.

The generator was bi-polar, 45 volts, with specially designed armature winding, and having a differential winding on the fields so that it would inherently regulate for almost constant output independent of the speed of the train. The generator was driven from the axle by means of a countershaft to which both generator and axle were belted, the idea in this being to protect the dynamo from vibrations of the car axle.

Another feature characteristic in this equipment was that it employed two storage batteries, one of which was charged while the other was being discharged in lighting the lamps. A twelve point switch was supplied which controlled the circuits of both batteries and generator and was operated by the trainmen in changing batteries when one battery had become exhausted.

The automatic switch was operated by a small solenoid shunted directly across the armature terminals so that it would close the generator circuit when it attained a voltage equal to that of the batteries, and opened the same when it fell below that of the batteries.

Electro-magnets were also employed to maintain proper polarity of the generator circuit.

The regulation as above mentioned was inherent in the generator itself, there being no other devices for regulating voltage.

In discussing this equipment it must be observed that it was not sufficiently adjustable for successful operation, the generator having a certain rated output irrespective of the light consumption. This is sure to cause very unsatisfactory operation of the batteries in connection with the equipment. From an operating standpoint the system would give satisfactory results if the generator was of sufficiently high output, in that the lamp regulation would be very good and the equipment fairly reliable. However, continued experience has shown the evils of a non-adjustable equipment and this apparatus is ready to be placed among the historical relics.

AXLE DEVICE OF AMERICAN RAILWAY ELECTRIC LIGHT CO.

This system was developed about 1896 and put into operation first on a trial car on the Pennsylvania Railway. It consisted essentially of a generator under the car, a regulator to operate field resistance, an automatic switch and a storage battery.

The dynamo was mounted inside the truck frame and geared direct to a large driving gear which was bolted to a split sleeve mounted on the middle axle of the six-wheel truck. The armature shaft was mounted in spring supported bearings to absorb shocks, etc., and was protected by dust-proof casings.

The regulator was the characteristic part of this equipment and was based on the principle of field rheostat control to compensate for variations of the generator speed. This was accomplished by means of a solenoid of heavy wire in series with the generator circuit, the magnetic flux in this coil being directly proportional to the generator current flowing. This coil would actuate an iron plunger, the motion of which would control the resistance in circuit with the field, thus raising or lowering the voltage as was necessary to restore normal conditions.

It was said that "the charging current is made to correspond with the number of lights in use so that there is no danger of short circuiting the battery." No explanation of this could be obtained, but it was presumably affected by a differential winding on the regulator coil.

The automatic switch consisted essentially of an electro-magnet mounted on a movable arm, such that when the generator pressure reached the proper value the magnetism set up in the electro-magnet, which was connected directly across the terminals of the generator, would close the generator circuit.

The proper polarity in the generator circuit was maintained by having two sets of brushes, one of which was operative in going in one direction and the other when the direction of the train motion was reversed.

This equipment apparently has the distinction of being the first to employ the principle of field rheostat control of generator voltage, which principle was later developed and improved and now forms the basis of operation of numerous modern axle devices such as that of the Consolidated Axle Car Heating Company, the Newbold Equipment built by the Adams & Westlake Co., the McElroy system, the new Moskowitz equipment, the Henry axle system, the Deutsch system, in this country, and the Dick Vicarina and Auvert in Europe.

McElroy System

MANUFACTURED BY THE CONSOLIDATED CAR HEATING CO. OF ALBANY, N. Y.

This is an equipment which has been recently developed and has not yet come into prominence, but has some points in its construction which are well worthy of consideration.

The generator is mounted directly on the trucks and is driven by a gear and pinion similar to those used on the motors of trolley cars: these being enclosed in a wrought iron gear case which is made dust-proof with leather packing.

Within the dynamo compartment is a mechanical device that determines the polarity of the circuit on reversal of the direction of motion of the car.

A battery auxiliary is supplied as in all other axle devices. This equipment is one of the type that controls by varying field resistance. The regulator is the characteristic part of the equipment and consists essentially of a compound solenoid controlling a motor, which in turn operates a field rheostat.

The compound solenoid is a part of the equipment that deserves special consideration. It consists essentially of a series coil of heavy wire placed in the battery circuit, and in addition to this a shunt coil which is connected directly across the generator terminals. Thus the control is one combined for voltage and current regulation and appears at least partially to eliminate the evils of the control by constant current.

By a proper adjustment of the ratio of ampere turns of the shunt coil to those of the series coil, the regulator may be made to protect the batteries from the destructive overcharge which is so often experienced when a constant current regulator is employed.

This, from a battery standpoint, is a very commendable improvement over the principle of control by constant current regulation and deserves special emphasis.

In explanation of the operation of this solenoid, let us assume actual operating conditions; there being 16 cells in the storage battery, the generator voltage then varies between 32 and 42 volts at different points of the battery charge. Accordingly the magnetic flux in the solenoid due to the shunt coil would vary proportionally to this pressure. This might be expressed as a variation from 320 to 420 ampere turns. Assuming that the series coil had been adjusted so that normal charging current would develop 110 ampere turns, this making a total number of 320 plus 110 equals 430 ampere turns in the solenoid when charge was first commenced. Now as the batteries become charged the voltage rises and the shunt coil magnetism is increased, thus requiring less magnetic pull from the series coil to regulate. It should be noted that the magnetic pull which balances the pull of the adjustable regulator spring is the sum of the magnetic pull due to the shunt coil combined with that due to the battery current flowing through the series coil, and that as the one increases the other must decrease to maintain equilibrium. When charged condition is obtained, the 430 ampere turns total in the solenoid would consist of 420 ampere turns due to the shunt coil, and only 10 ampere turns due to the series coil, thus the charging current has been reduced to only 9% of its normal maximum value. It is obvious that by a suitable proportion of ampere turns due to the series and shunt coils the battery overcharge may be reduced to any desired value.

In regard to the detail operation of the controlling apparatus, the compound solenoid moves an iron plunger back and forth, which in turn makes contact through the armature of a small motor, causing it to rotate backward or forward, cutting in or out a field rheostat as may be required to regulate the generator voltage. A lamp resistance is also inserted in each lamp circuit by this motor when the generator becomes operative. The motor serves also to close the generator circuit when the critical speed is attained, thus an automatic switch is not required.

In this regulator the motor runs only when regulation is necessary, so that a minimum wear on moving parts is obtained.

In discussion of the equipment it must be said that it appears to be reliable and entirely automatic. From a standpoint of battery operation it is an admirable equipment and will likely give a much longer life to the batteries than numerous other axle devices.

In regard to lamp regulation, however, the equipment is a very poor one. It is impossible to build a magnetic solenoid to operate between an upper and a lower limit without allowing a probable error of 5 or 10 per cent. In a "current regulator" this variation of current is readily absorbed by the battery without causing an appreciable variation of lamp voltage, but in a "voltage regulator" this 5 or 10 per cent. variation is received entirely by the lamps. It is true, a certain definite lamp resistance is inserted each time the generator becomes operative,—this to compensate for the difference between voltages of battery discharge and charge, but no definite lamp regulation is attempted. Due to the series coil of the regulator being placed in the battery circuit, the batteries will be charged entirely irrespective of whether or not the lamps are lit, so that though the lamp resistance be in circuit the rise in charging voltage of the battery will cause a proportionate rise in voltage at the lamps.

This could be largely eliminated by a slight modification of the regulator solenoid, if another series coil were added to the solenoid and this placed in the lamp circuit so that when the lamps are turned on the current through this coil will create a magnetic flux which will largely replace that of the battery charging current.

This would cause a large decrease in the battery current when all the lamps are turned on, and would accordingly require that the charging be done largely during the day. This in many cases would be a serious disadvantage, but when installed on a car making at least a part of its run during the day, it might be made to operate satisfactorily.

The United States Axle Equipment

This equipment is one recently invented by Mr. Morris Moskowitz, who has for years been associated with the development of various types of axle lighting devices, one of which has been described on page 16.

The equipment consists essentially of a generator, pole changer, storage battery auxiliary, regulator, automatic switch, and lamp circuits within the car.

The *generator* is of a four pole, shunt wound, type, encased in a dust and water-proof steel casing, provided with proper hand holes for inspection. It is driven by a belt from a large axle pulley and is suspended from a shaft which is supported by a heavy iron framework from the forward truck sill. This shaft is mounted on springs to relieve the generator of the truck vibration.

A *pole changer* is fitted to the end of the generator shaft to provide proper polarity irrespective of direction of car motion. This is effected by a dog fitted into a transverse slot on the armature shaft which throws a reversing switch; the range of action of this dog being limited to 90 degrees by means of a steel guide. For speeds above four miles per hour this dog becomes inoperative, being drawn back into the slot by the centrifugal action of a heavier portion of itself on the opposite side of the center of rotation, thus eliminating excessive wear.

The *regulator* is a characteristic part of this equipment and is of the type which maintains constant generator current. The principle upon which it is based is that of a solenoid in series with the generator armature controlling the variable resistance of a pile of carbon discs in multiple with the generator field, so as to decrease the generator field current to compensate for rise in train speed, and *vice versa*. The magnetic pull of the solenoid is balanced by the adjustable pull of a spring.

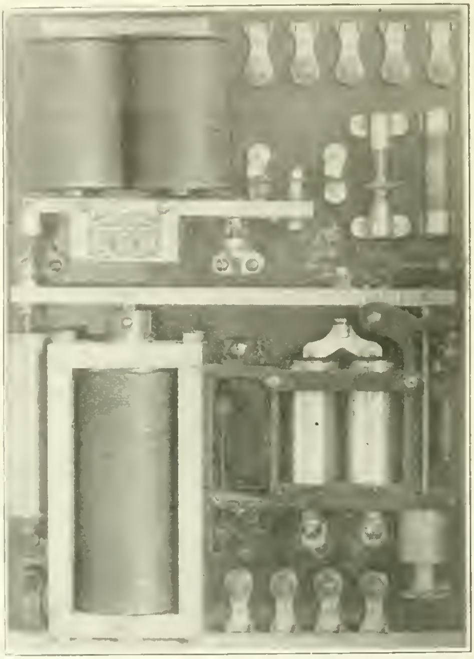

Plate II.—Regulator of the Axle Equipment of the U. S. Light and Heat Co.

This is a very simple and apparently reliable regulator in that no movements of the parts are required except the slight motion of the floating plunger in the solenoid, necessary to produce the proper pressure upon the pile of carbon discs.

In that the field current is controlled by variable resistance in multiple with it, there is an external resistance added in the combined circuit so that the total current through the field and carbon discs together is maintained practically constant.

In order to provide lamp regulation, a lamp resistance is inserted by the regulator when regulation first begins. This is again automatically short circuited when the generator is cut out.

The *automatic switch* is similar in principle to that described on page 18. but is of radically different construction in that instead of having four little solenoids—two stationary and two movable, it consists of two large compound stationary solenoids of very robust construction, shown at the top of the accompanying figure.

In discussion of this equipment it may be said that it has the advantage of simplicity in providing proper regulation and will do so quickly and accurately. This is a very important feature in such an equipment and should be given special emphasis.

But, on the other hand, the equipment inherently contains all of the imperfections common to constant current regulators, as discussed on pages 111 to 120.

This type of lamp voltage regulation, while it cares for the variations of battery voltage from the conditions of discharging while train is stopped to that necessary to produce a slight charging current while running, it does in no way care for the variation of battery voltage due to the condition of battery charge, as considered more fully on page 125, nor is the regulation independent of the number of lamps in use.

The generator is of rather small construction in comparison with generators used in this work.

The pole changer may be said to be of excellent construction in that it is extremely simple and has no parts of excessive wear.

Everett Regulator

This type of regulator was recently devised by Mr. S. W. Everett of the Santa Fé Railway. It was designed particularly for the purpose of obtaining more satisfactory service with an older type of axle equipment which that railway has been operating for some time.

It consists essentially of two variable shunts placed in parallel with a field rheostat, Plate III.

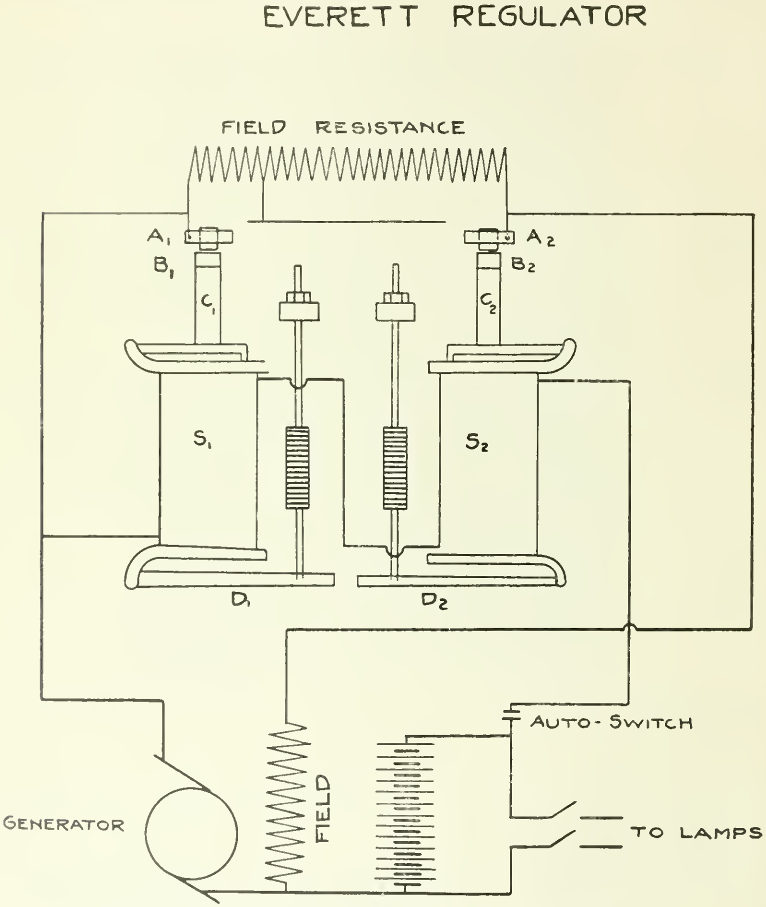

Plate III.—Showing Design of Everett Regulator.

These variable shunts consist of carbon buttons, A_1, B_1, and A_2, B_2, which are operated directly by the floating plungers C_1 and C_2 in the solenoids S_1 and S_2.

The operation of the regulator is as follows: when the car is at rest the contact buttons will be held firmly together by the springs T_1 and T_2, these causing a minimum resistance in the generator field circuit. When the speed increases so that the automatic switch closes, the generator current flowing through the coils S_1 and S_2 creates a magnetic pull on the plungers C_1 and C_2, thus lessening the pressure on the carbon buttons A_1 B_1 and A_2 B_2 and increasing the total resistance in the field circuit which causes a corresponding decrease in the generator field current which is necessary to compensate for rise in train speed.

The tension on the springs T_1 and T_2 is so adjusted that the contact A_1 B_1 is first operated, then as the train speed goes still higher, that contact being open, the control is effected by the varying resistance of the contact A_2 B_2.

The regulator has many of the advantages of simplicity found in the previous equipment described, and is reported to be giving satisfactory service on the few cars on which it is installed. It has, however, all of the inherent disadvantages of the constant current regulator as described more fully on page 111.

THE DEUTSCH SYSTEM OF AXLE LIGHTING

This equipment was recently invented by Mr. I. Deutsch. It operates on the principle of constant current control by means of a large solenoid placed in the generator circuit which controls the operation of a field rheostat to compensate for variation in train speed. In the manner in which the rheostat is operated this equipment is a radical departure from the others described, in that it is operated by the air pressure from the brake pipes on the train, the supply of which to the rheostat operating mechanism is governed by the controlling solenoid.

The generator is located beneath the car but is not mounted directly on the car truck as is the common American practice, it being in this case fastened to the under beams of the car body. The generator is driven from the axle by means of a bevel gear transmission, there being a universal joint and telescopic shaft supplied to compensate for the motion of the truck on rounding curves.

There is apparently no special lamp regulation attempted other than that of controlling the generator current to a constant value.

An automatic switch, so essential in this type of equipment, closes the generator circuit when the proper voltage is attained, and opens it again when the train speed falls to such a value that the generator voltage falls slightly below that of the battery.

CHAPTER III

TESTS OF VARIOUS EQUIPMENTS

Test of Curtis Turbo-Generator Set

The test of this equipment was made on trains Nos. 1 and 6 of the Chicago, Burlington and Quincy Railroad, running between Chicago and Denver; the equipment consisting of a 25 K. W. Curtis turbo-generator set mounted in the front end of the baggage car, there being an auxiliary of two sets of batteries in connection, one located under the baggage car and the other beneath a Pullman car at the rear of the train. The turbine receives its steam from the locomotive through a pipe line located beneath the cars and a flexible hose connection between cars, there being a reducing valve at the locomotive which reduces the steam pressure from boiler pressure to 80 pounds per square inch at the turbine.

The turbo-generator set is one manufactured by the General Electric Co. and is of 25 K. W. capacity, type C–2–25–3600–Form–T, amperes 200. The turbine is equipped with a governor which automatically regulates the speed by opening or closing poppet-valves controlling the steam supply. The steam after leaving the turbine exhausts through a steam funnel into the air above the car, the funnel serving to drain back the water in the steam, thus preventing an undue collection of ice on the cars in the winter time.

The *switchboard* is conveniently mounted in the dynamo compartment and contains an ammeter and voltmeter of the Weston type, two gauges, one for reading the pressure of the steam as delivered to the turbine and another of lower scale to register the pressure as delivered to the train pipes for heating the cars.

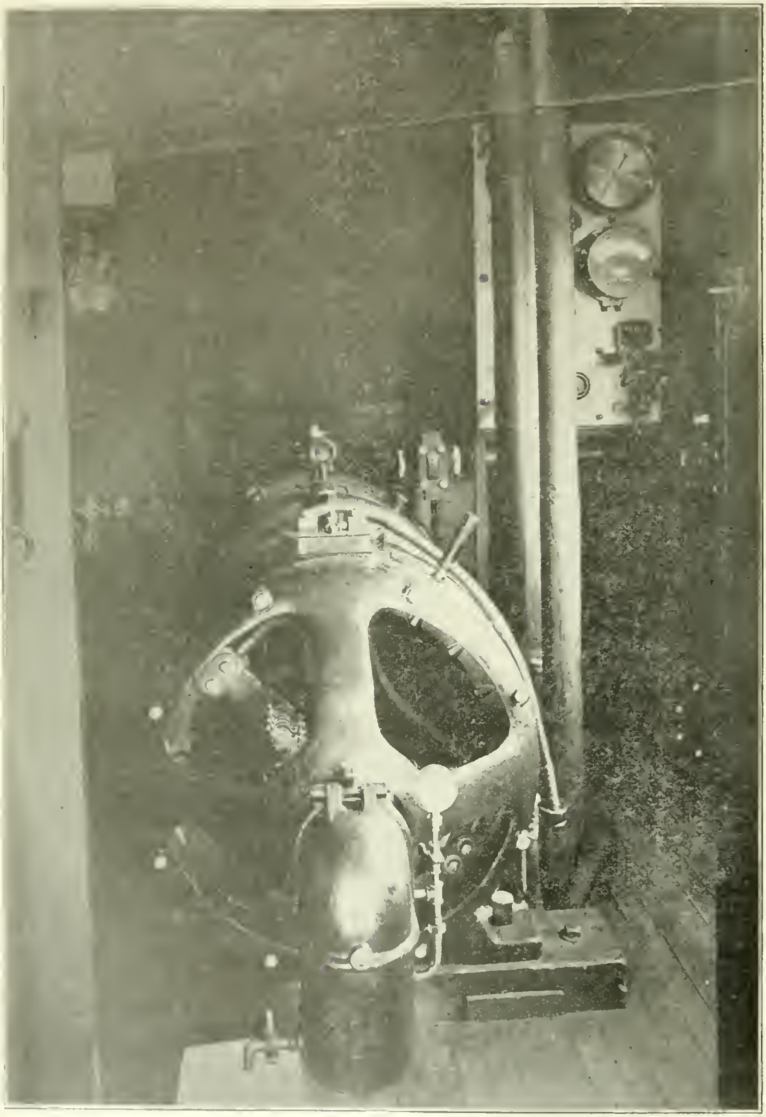

PLATE IV.—CURTIS TURBO-GENERATOR SET, C. B. & Q. RY.

The switchboard also contains an automatic circuit breaker designed to protect the generator against both overload and reverse current. The under load (reverse current) attachment is provided so that in case the steam pressure is shut off and the generator becomes inoperative, the circuit will be automatically opened as the speed decreases, thus preventing the generator being driven as a motor by the batteries.

The *batteries* consist of two sets, one located on the baggage car and one on a rear Pullman car. They are of the type 13–E made by the Electric Storage Battery Co. and are of 240 ampere-hours capacity, there being 54 cells supplied to each battery. These batteries are floated directly on the line, thus adding to the simplicity of the system in that they require no switches to be thrown to place them on the line when the turbine is cut off, but they are always ready for the service of supplying current to the lights.

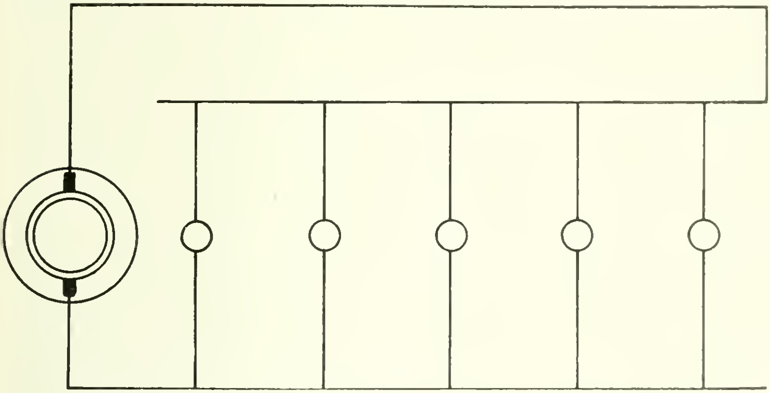

PLATE V.—SHOWING ARRANGEMENT OF THE TRAIN LINE.

The *train line* is arranged in the manner known as the return loop or Wirderman construction, and consists essentially of three wires running throughout the length of the entire train, being located in the roofs of the cars; the positive wire, as illustrated in Plate V, running to the rear of the train from whence it loops back along the same path to the forward car of the train, the lights and batteries being connected between this return loop and the third wire which is connected directly to the negative brush of the armature. The object of this construction is to obtain a more uniform distribution of potential to the lamps along the line.

There is another feature in the train line construction, which, though common in train wiring, deserves special emphasis; it is that the two feeding wires are crossed within each car and also between every two cars. This is to preserve proper polarity to each of the wires within the car. The necessity for this is best shown by a comparison of the three figures of Plate VI. In Fig. I is shown the train line as in operation. It is obvious that no matter which end of the car (B) is forward the same polarity of the generator will be presented to the batteries located on that car. It is also readily seen that, if the train had been wired straight as per Fig. II, a battery being located on the middle car, and that car were turned end for end as in Fig. III, the positive generator lead would be presented to the negative terminal of the battery and the negative terminal of the battery to the positive lead from the generator; thus causing a direct short circuit of the generator and battery through each other.

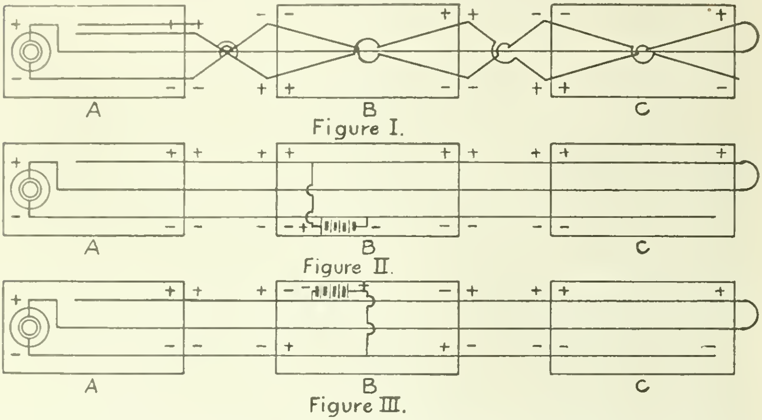

PLATE VI.—ILLUSTRATING THE CROSSING OF THE TWO FEEDING WIRES.

The *connectors* between cars are of a special type designed for this purpose, consisting of male and female parts, each of which has three insulated connections for accommodating the three train wires.

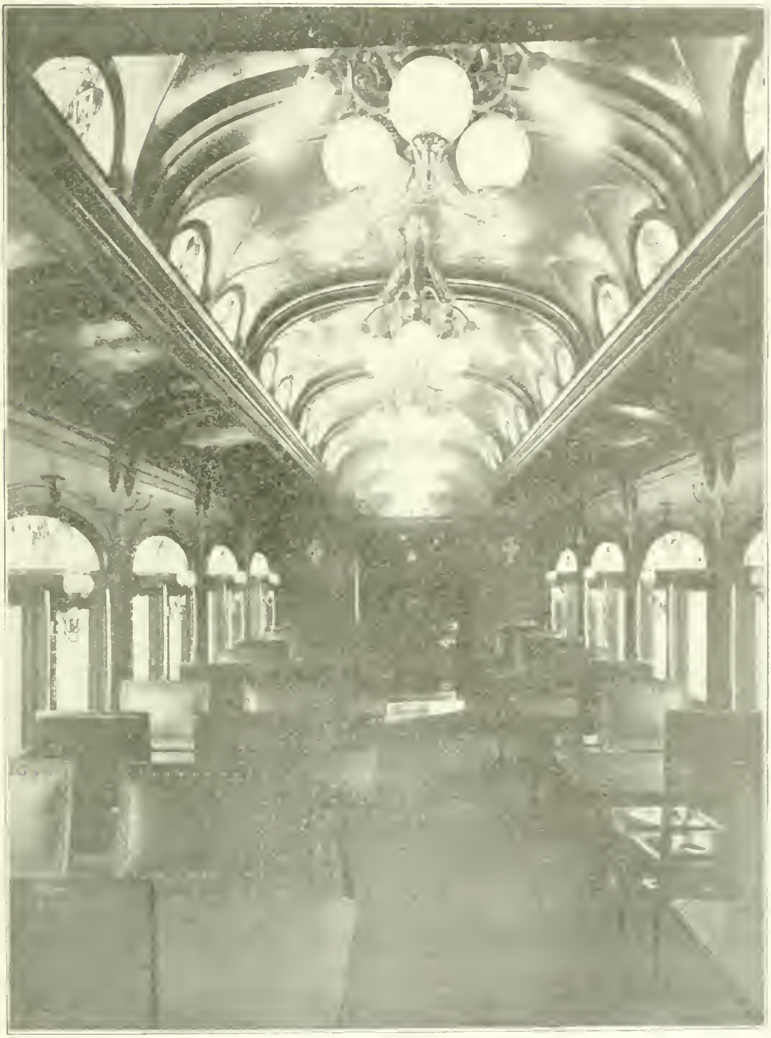

Plate VII.—Dining Car, Denver Limited, C. B. & Q. Ry.

There is a hard rubber block between the two positive leads to insure against putting in the male connector upside down. A thumb screw clamps the male solid after it is inserted into the female block and insures good and permanent contact. The leads between cars are of heavy flexible copper cables and are looped up and fastened to one side of the passageway, so as not to interfere with the traveling public.

Each car is equipped with an individual switchboard containing switches for each of the lighting circuits, as well as fuses for the same, and in cars containing batteries there are switches for the battery and the train line.

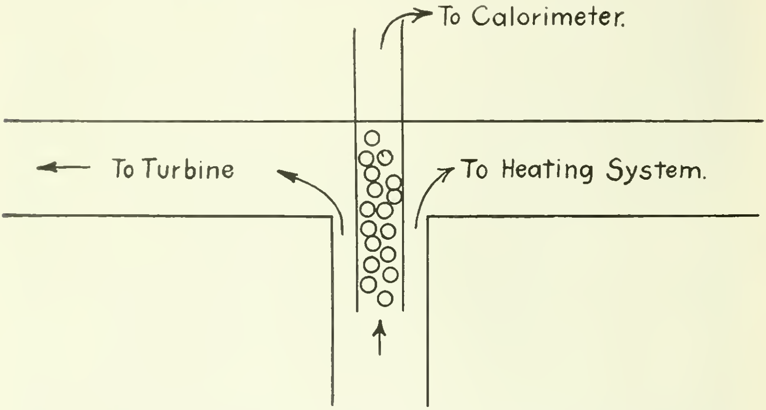

Plate VIII.—Showing Calorimeter Top, Curtis Turbine Test.

An electrician is placed in charge of the equipment and is on the train throughout the whole trip, his duty being to maintain the voltage constant and to care for any emergencies in the operation of the equipment as well as to maintain proper steam pressure on the train heating system.

Method of Test

Two distinct tests were made of this equipment:—one a road test to determine operating conditions of the equipment and the other, a steam consumption test to determine the amount of steam consumed from the locomotive boiler in the operation of the equipment.

For the *road test* the turbine was equipped with a calibrated steam gauge, and a separating calorimeter to determine the pressure and quality of the steam. The pressure gauge was located in the pipe line about a foot from the turbine steam chest. The separating calorimeter tap was located in a "T" pipe connector, illustrated in Plate VIII, at the point where the steam is first carried into the engine room by the pipe line from the locomotive boiler, and before it has passed through the separator, so no consideration was made of the separator water, this being all included in the moisture of the steam as indicated by the calorimeter.

In order to determine the electrical operation of the equipment, a calibrated ammeter was placed in the generator circuit and a calibrated voltmeter was connected across the terminals of the generator. The speed of the generator was determined by means of a stop watch and speed indicator. Readings were taken at 15 minute intervals throughout the whole time of generator operation. When the lights were on the batteries, readings of voltage and current at each battery were taken, also the total time of operation of the same.

In addition to the above data the pressure of oil on the bearings was noted occasionally, the gauge already installed on the turbine being used for taking such readings.

Yard Test for Steam Consumption

After equipping one of the turbine sets for a test in the yards at Chicago it was found that not sufficient cooling water could be obtained to condense the steam used. Accordingly it was determined to make this test at the steam laboratory of the University of Wisconsin where there has this year been installed a turbo-generator set identical with the one tested on trains Nos. 1 and 6. In making this test the turbine was operated under the same voltage as is usual on trains Nos. 1 and 6.

A surface steam condenser of the Blake type of a capacity of 2,000 pounds of steam per hour was connected up to the exhaust pipe and used to condense the steam used in driving the turbine. This condensed steam was run into tubs where it was weighed on standard Fairbank's platform scales at intervals of exactly five minutes each, so that the steam used for each five minutes might be determined.

The *load* was applied to the generator by means of a water box, and voltage and current were measured by calibrated Weston instruments.

The pressure and quality of the steam were determined by a pressure gauge tapped in very near the turbine and by means of a throttling calorimeter tapped into a vertical section of the pipe at the turbine. The back pressure was read on a manometer tube tapped into the exhaust pipe. The speed was determined by means of a stop watch and speed indicator. Data were taken of each of the above at the various loads of ¼, ½, ¾, full, and 1¼ load for the several steam pressures of 60, 70, 80 and 90 pounds per square inch, respectively; readings being taken for periods of 30 minutes each, keeping the steam pressure and load constant.

Discussion of Results

Referring to the curves on Plate IX, the most striking result of the test on the road is the fact that the generator load is never above 17 K. W. and the average load is less than 11 K. W., while the generator set is of 25 K. W. capacity. There are, however, several reasons for the selection of this equipment of large capacity, in regard to which it may be said by way of introduction that the efficiency of operation is not merely the relation of out-put to in-put, but in service on the railroad a number of other considerations enter in to make efficiency or cost of operation of secondary importance. For instance, it is necessary that the railroad be prepared to handle very heavy traffic at certain rush seasons, in many cases doubling the size of its passenger trains, thus requiring a proportionally heavy lighting capacity, which, though lasting for a few days only, must still be taken into consideration in determining the capacity of equipment.

Still another condition which warrants the use of a set of such large capacity is the low steam pressures, say 60 pounds per square inch, which often occur, the turbine then being able to

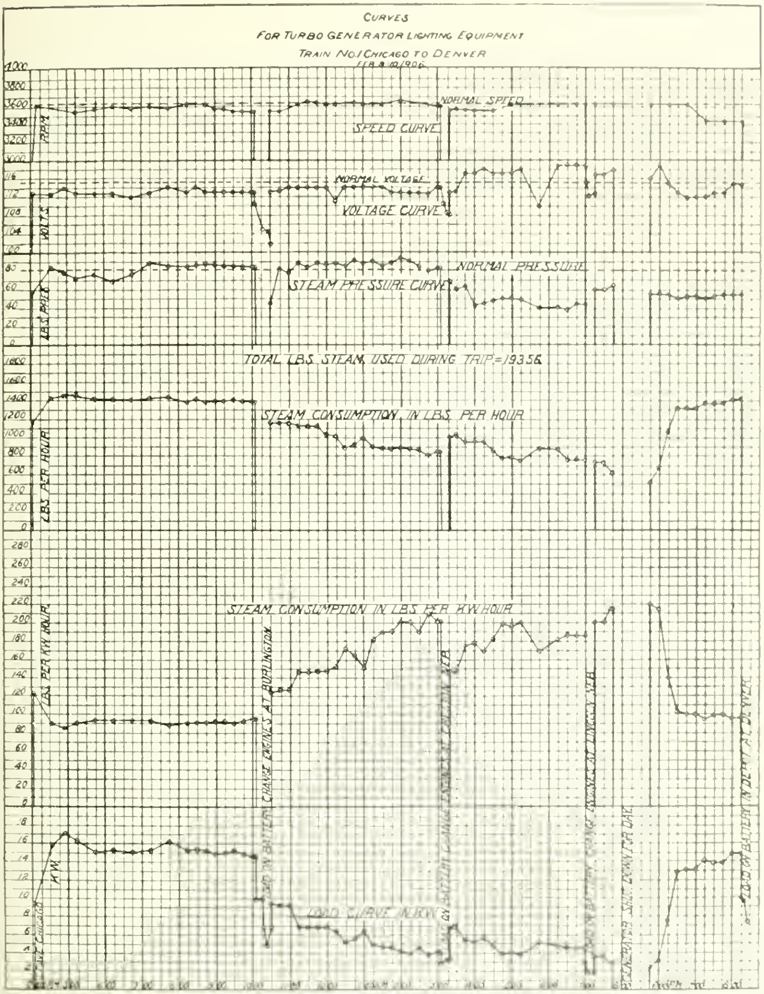

PLATE IX.—CURVES FOR TURBO-GENERATOR LIGHTING EQUIPMENT.

deliver only $\frac{1}{2}$ or $\frac{3}{4}$ of its normal full load. Under such conditions a 25 K. W. set will still carry the load of lights in a train, but a 15 or 20 K. W. set would not be able to carry the load of lights. Another fact which deserves attention is that the gross steam consumption over the whole trip does not vary as much as might be expected. from full load to the lighter loads, as shown by a consideration of the curve of steam consumption, plotted in pounds of steam consumed per hour, Plate IX. the maximum variation of gross steam consumption being from 1,460 pounds per hour at 17 K. W., to 550 pounds at 2.5 K. W.

It is readily seen from a comparison of curves of load and of steam consumption per K. W. hour that the steam consumption per K. W. hour varies inversely as the load; this tending to make the total steam consumed more nearly constant at the various loads.

Discussion of Steam Consumption Test

Referring to the curves of Plate X. the results of the steam consumption test show some remarkable features. In the first place it was found that the steam consumption curves for all the pressures employed were almost identical. that is, that for variations of steam pressure between 60 and 90 pounds per square inch the steam consumption is independent of the steam pressure. This is indicated by the fact that all the points determined lie on the same curve. The only explanation for this peculiar result that can be offered is that a throttling action may take place in the governor. which tends to maintain the pressure on the nozzles more or less constant. irrespective of the pressure in the steam pipe.

The steam consumption is higher than is to be expected from a reciprocating engine of a similar capacity. but an explanation of that fact is not within the limits of this investigation.

This matter of high steam consumption was taken up with the General Electric Co. A representative was sent to Madison to inspect the turbine which had been tested, and he replaced the steam nozzles with some of a newer type. and a following test was made.

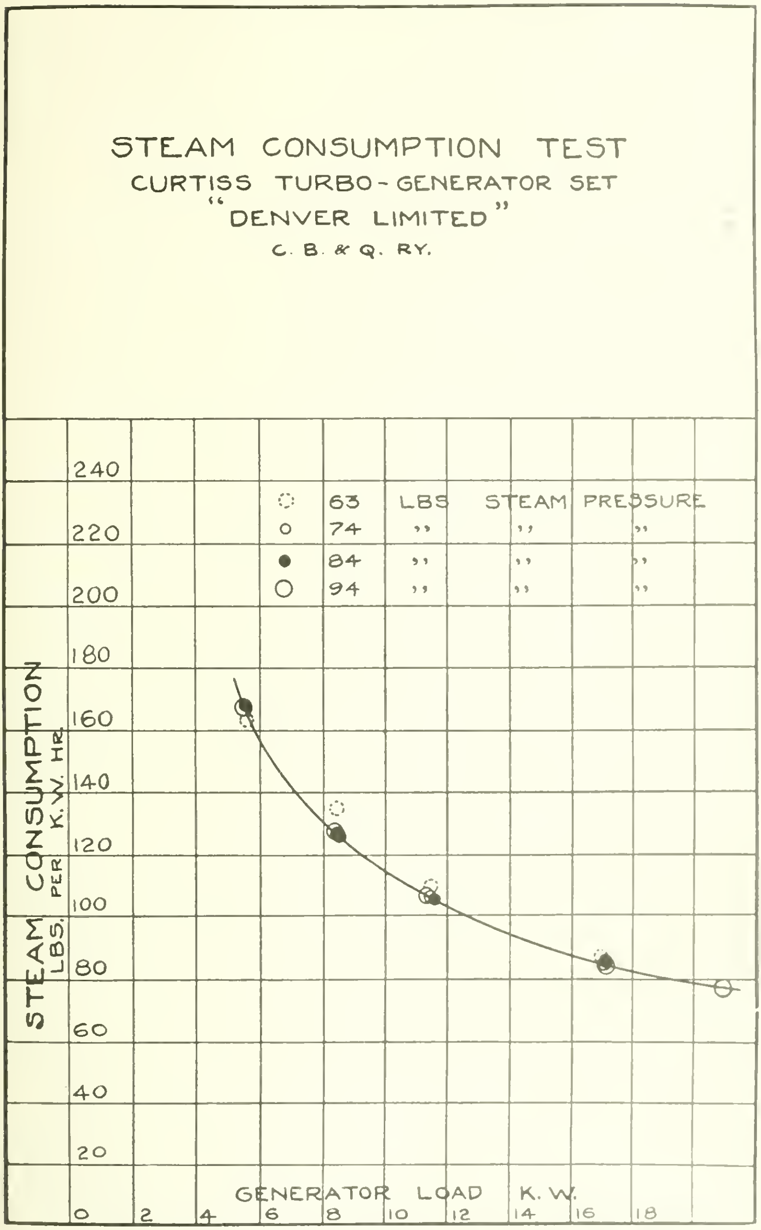

PLATE X.—CURTISS TURBO GENERATOR SET. CURVES OF STEAM CONSUMPTION.

Readings were taken at five minute intervals during a run of one-half hour. The turbine had been in operation before the test started so that all parts were thoroughly warmed. The results were as follows:

Average volts	125.4
Amperes	200.0
Speed R. P. M.	3403.
Steam pressure, pounds per square inch	80.
Quality of steam, per cent.	98.3
Total steam consumed, pounds	846.5
Average load, K. W.	25.08
Total wet steam consumed per hour, lbs.	1693.
Total dry steam consumed per hour, lbs	1662.
Total dry steam consumed per K. W. hour, lbs	65.4
Total dry steam consumed per E. H. P. hour, lbs	49.5

This shows a considerable improvement in the steam consumption over the conditions found in the first test, (about 8 per cent. at full load) and so due reference is made to it here, showing the possibility of the turbine with the improved nozzles. Accordingly, the nozzles on the turbines in the Burlington Railroad equipments have been replaced by the newer ones since our tests were made.

According to our records, 19,356 pounds of steam were used in lighting the train from Chicago to Denver, which is approximately three per cent. of the total water supplied to the locomotive boiler as indicated from the number of tank fillings.[1]

Westinghouse Engine Generator Set.

On North Coast Limited, Northern Pacific Railway, St. Paul to Portland, Oregon, December 23 to 31, 1905

The equipment consists essentially of a Westinghouse Standard engine located in the forward end of the express car which drives a generator in direct connection, receiving its steam from the locomotive through a pipe line and flexible hose connections, there being an automatic pressure reducer on the locomotive which is supposed to maintain a pressure of 80 pounds at the generator set.

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[1] The complete data of this test can be found in the graduating thesis of A. U. Hoefer and Edgar Kearney, University of Wisconsin, 1906.

An auxiliary storage battery is supplied to each car except the mail and express cars. These batteries were not floated on the line continually as was found in the equipment on the Denver Limited in the test previously described but were wired so that they could only be thrown on one circuit of lights, and were not in connection with the train line except when they were thrown on to light the lights or when they were charged at night.

The batteries received a charge each night when most of the lights throughout the train had been turned off, by raising the generator voltage to 115 volts and maintaining it constant at that value for several hours. This provided 2.3 volts per cell which will if continued long enough very likely fully charge the batteries.

The batteries are also fully charged to 130 volts once a week when the train is being cleaned in St. Paul, the current being kept constant at 50 amperes.

The *train line* was of the three wire return loop system described on page 29 of the previous test and will not be considered further here. An electrician who remains on the train over the whole round trip, is placed in charge of the equipment.

METHOD OF TEST

The method of testing was very similar to that of the previous test. A road test was made to determine the operating conditions, and this was supplemented by a steam consumption test in the yards under the conditions of operation experienced on the road.

In the *road test,* readings were taken at fifteen minute intervals of generator speed, voltage and current, steam pressure, steam quality, separator water and indicator cards.

The first five mentioned were all taken by means of calibrated instruments from the laboratory of the University of Wisconsin.

Separator water was tapped off from the "Cochrane" separator supplied permanently to the engine, and weighed on a spring balance. The engine was indicated by means of a special link mechanism consisting of a pair of cranks, connecting rod, and piston rod sets in the exact relation as existed between those inside the engine. This mechanism was then bolted to the end of the shaft so that the small piston rods would reproduce the motion of the engine piston rods within the engine. The indicators were placed on top of the cylinder heads in place of the poppet relief valves and the indicator motion was transmitted from the link mechanism by cords. A heavy spring was added to the indicator cord so as to keep it very tight, to care for the vibration due to the high speed of 400 R. P. M.

The *yard test* consisted in making a measurement of the steam consumption under conditions as they were found on the road test. The steam from the engine exhaust was run into a surface condenser and collected in tubs and weighed on platform scales. Each test consisted of a run of twenty minutes duration, during which time the load and steam pressure were kept constant, these tests being made for loads of ¼, ½, ¾, and full load and for the different steam pressures of 42, 50 and 85 pounds per square inch, respectively.

The road test was made in duplicate by two different parties on two different trains, while the steam consumption test was made for only one equipment.

The plotted curves of the road test which are here exhibited are for one night's operation on one equipment only, this set being selected as typical.

CAR NO. 241

Night.	K. W. hrs., load.	Total wt. of steam.	Separator water.	Av. lbs. stm. per hour.	No. hrs. run.	Av. load in K. W.	Av. steam. lbs., K. W. hr.
1 West.	149.85	15,930	720	980	16.2	9.22	106.4
2 West.	161.5	15,750	420	900	17.5	9.24	97.5
3 West.	144.1	15,740	400	1,000	15.7	9.16	109.2
1 East.	156.5	15,860	717	1,005	15.7	9.25	101.0
2 East.	154.1	11,480	635	730	15.7	9.7	75.4
3 East	159	15,030	947	1,002	15.0	10.6	94.7
Total.	925.05	89,790	3,839	936	96.0	9.65	97.3

CAR NO. 237

Night.	K. W. hrs., load.	Total wt. of steam.	Separator water.	Av. lbs. stm. per hour.	No. hrs. run.	Av. load in K. W.	Av. steam lbs. K. W. hr.
1 West	109.7	10,530	586	660	16	6.87	96
2 West	121.4	13.750	592	860	16	7.59	113
3 West	120.4	15.810	623	1.003	15.75	7.65	131.2
1 East	145.2	16.300	934	1.002	16.25	8.95	112.2
2 East	119.4	13.775	666	950	14.5	8.24	115.4
3 East	114.2	15.460	731	1.030	15	9.63	107.3
Total	730.3	85.625	4.132	916	93.5	8.17	112

DISCUSSION OF RESULTS

Attention should first be called to the results of the yard test shown in Plate XII. It is seen that the steam consumption for 42 pounds steam pressure is much higher than it is for 83 pounds pressure at the same load. This is due to the fact that the governor on the engine is one for constant speed and in its efforts to maintain this constant speed at the low pressure it increases the admission. Some cards taken at low pressure showed admission of steam to the cylinders for more than three-quarters of the stroke.

The steam consumption at the higher steam pressures is reasonable and about what might be expected from the type of engine.

Referring to the road test curves on Plate XI, attention should be called to the high peak in the steam consumption curve at 6:00 P. M. This is due to the fact that the load was great and at the same time the steam pressure was very low, as is shown by the corresponding curves.

There is an interesting note in connection with this fact. The locomotive engineman in his efforts to relieve his own engine, throttles the steam connection to the generator set, but in fact in doing so he only increases the drain he intended to lessen. If he had given the generator full pressure instead of throttling it lower, he would have really lessened the steam consumption and at the same time afforded better operation of the lighting equipment. It should also be noted that the steam consumption

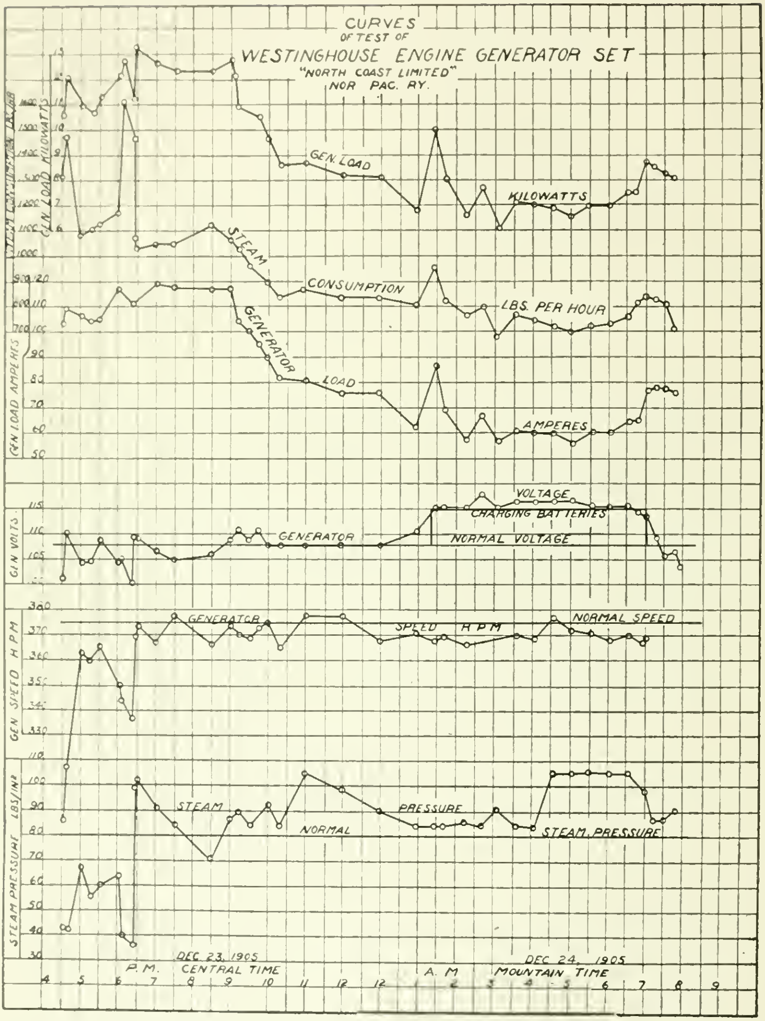

Plate XI.—Curves of Test of Westinghouse Engine Generator Set, Nor. Pac. Ry.

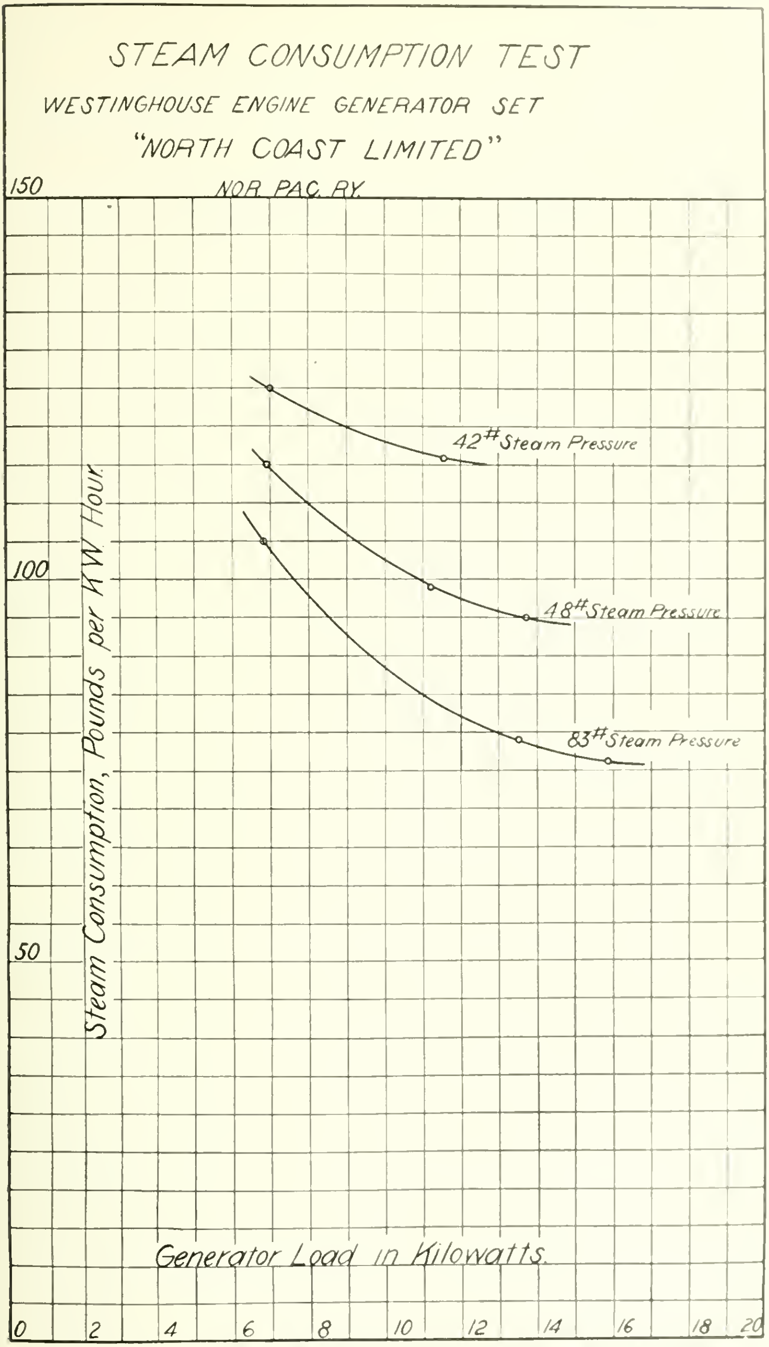

Plate XII.—Steam Consumption Test, Westinghouse Engine Generator Set.

does not follow the load curve directly, but tends to remain more constant.

Both the engine speed and generator voltage are affected by variations in steam pressure and are seen to follow the steam pressure curve almost directly, especially where low steam pressure occurred. The generator output is often affected as shown by the curve at 6:00 P. M. This fact is one of the main causes of failure of this equipment in that the engineer throttles the steam supply and causes the generator to fail in maintaining proper lighting of the train and at the same time really increases the drain on the locomotive. This point cannot be given too much emphasis, as it is due to a wrong conception on the part of the enginemen and should be corrected.

It is seen by reference to the test on the Pioneer Limited, C., M. & St. P. Railway, that a very similar condition exists there.

In regard to the method of charging batteries on the road by raising the voltage to 2.3 volts per cell, it must be said that this seems to be about the best way to keep them up during the trip, though it is very destructive of the lamps lit at that time, the high voltage causing them to be strained, which spoils them for operation at the normal voltage.

The method might be adopted of charging in the daytime, but that would involve an extra run and additional drain on the locomotive and would be liable to cause trouble with the enginemen.

The charge every week at St. Paul, in which the batteries are fully charged, is sufficient to keep the batteries from becoming permanently sulphated.

In regard to the steam connections, it must be said that considerable trouble was experienced. The flexible connection between the cars consisted of a combination of the Moran metallic coupling and the Martin flexible joint. We found the greatest trouble in the Martin joints. When the Moran coupler was properly locked it gave little or no trouble. The Martin joint is in the form of a ball and socket joint, made up of a bell shaped piece, which is inserted in a Vulcabeston packing ring, and is free to move more or less in all directions.

There were eight of these connections between the dynamo and locomotive which were in constant need of attention.[2]

Test of Westinghouse Engine Equipment

Pioneer Limited, C., M. & St. P. Ry.

The equipment under consideration is very similar to that of the two tests on the Northern Pacific and the Chicago & Northwestern railways, consisting of a high speed Westinghouse Engine Generator Set mounted in the forward end of the baggage car and supplied with steam from the locomotive at 80 pounds pressure per square inch.

The C., M. & St. P. Railway was the first to adopt this method of train lighting. One of the earlier equipments consisted of a separate car known as the "Light and Heat Tender," which in the winter months supplied both light and heat for the train, but was in the summer months replaced by an ordinary baggage car equipped with a generator set. This gave satisfactory results but was ultimately abandoned (in that it required an extra car and attendant) and the duties of supplying light and heat were placed upon the locomotive, resulting in the present equipment.

The equipment tested consisted of a 25 K. W. generator set placed crosswise of the end of the car to reduce the train vibration caused by the set. This is at times very objectionable and can be felt often times throughout the entire length of the train, hence this location of the generator set is made to minimize this. The shafts of the baggage car generating sets of the Northern Pacific and Chicago & Northwestern roads, are placed longitudinally within the car. A storage battery is supplied as an auxiliary to maintain the lights when the locomotive is disconnected at engine changes.

The method of train wiring is similar to that of the Denver Limited described on page 30 and will not be considered further.

The equipment is placed in care of the baggageman who looks after the generator set, etc., in the baggage car, but the care of the train line is placed in the hands of the brakemen on account of the other duties of the baggageman making it impossible for him to leave his car.

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[2] For the complete data of this test refer to the graduating theses of W. [illegible] Bertke and I. L. Reynolds, University of Wisconsin, 1906.

METHOD OF TEST

In making the test of the equipment two round trips were made with the equipment between Chicago and St. Paul to determine the operating conditions on the road. This test was supplemented by a steam consumption test in the yards at Chicago, under conditions similar to those found in operation on the road.

In the road test, additional data were taken in connection with the heating of the train, but this is not within the limits of this thesis so will not be considered here.

In connection with the operation of the lighting equipment, however, data were taken of the following:—generator load voltage and speed, and engine steam pressure, quality of steam and quantity of separator water. The engine also was indicated in the following manner:

The safety plugs were removed and a stuffing box inserted through which a rod was passed and bolted to the piston head, thus transferring the motion of the piston head to the indicator motion which consisted of an ordinary link mechanism. Special holes were drilled in the cylinder heads to accommodate the indicators.

In the steam consumption test the steam consumed was determined by operating the set at constant load and constant steam pressure over a period of 15 minutes, readings being taken at five minute intervals of the steam used, steam quality and pressure, generator speed, voltage and current. The steam was condensed in a surface condenser and weighed in tubs on platform scales. Indicator cards were also taken at five minute intervals.

The results of the steam consumption test are given on Plate XIV.

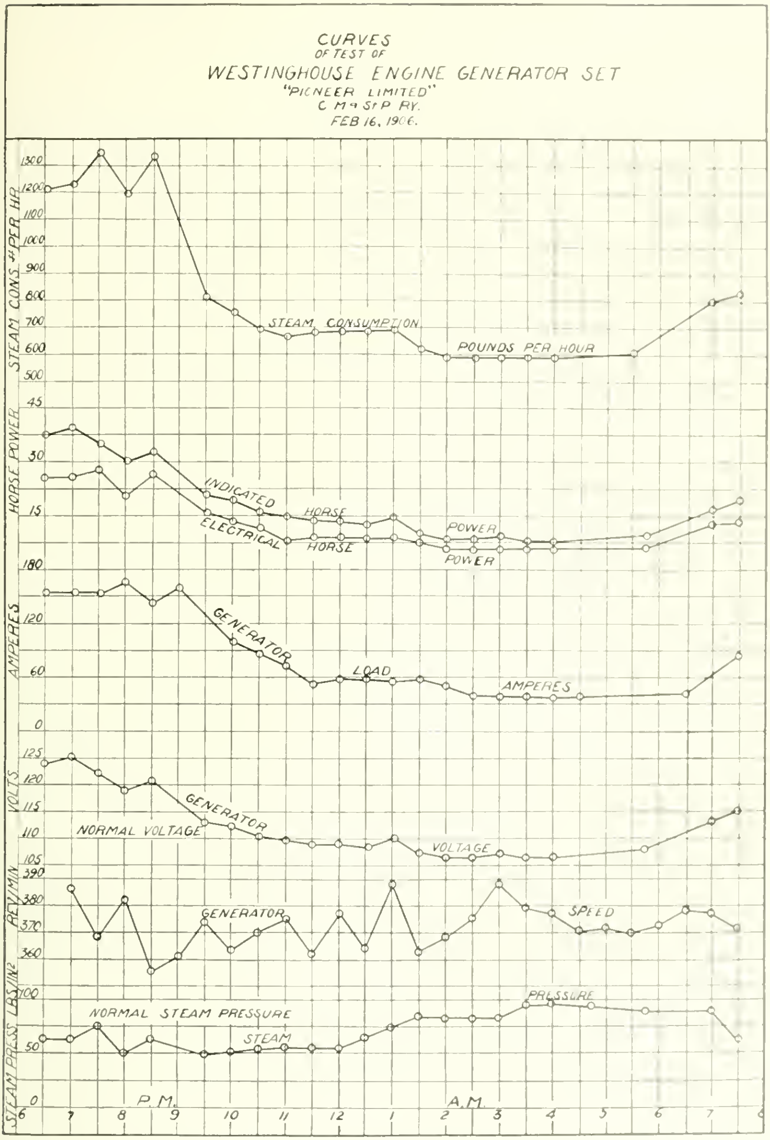

Plate XIII.—Curves of Test of Westinghouse Engine Generator Set, C. M. & St. P. Ry.

Results of Test

1st trip. Chicago to St. Paul, Feb. 14, 1906:
Average steam pressure .... 92 lbs. per sq. in.
Average load of lamps .... 8.7 K. W.
Average steam consumption ....690 lbs. per hr.

2nd trip. St. Paul to Chicago, Feb. 15, 1906:
Average steam pressure ....108 lbs. per sq. in.
Average load of lamps .... 8.9 K. W.
Average steam consumption ......580 lbs. per hr.

3rd trip. Chicago to St. Paul, Feb. 16, 1906:
Average steam pressure .... 75.7 lbs. per sq. in.
Average load of lamps .... 9.8 K. W.
Average steam consumption ......780 lbs. per hr.

4th trip. St. Paul to Chicago, Feb. 17, 1906:
Average steam pressure .... 90 lbs. per sq. in.
Average load of lamps .... 9.5 K. W.
Average steam consumption ......770 lbs. per hr.

Discussion of Results.

In discussion of the results of this test it must be said that the operation is very similar to that experienced with the other similar equipments as discussed on page 41, except for the fact that this one shows somewhat more economical operation as seen by the comparison on Plate XLVI.

The high steam pressure of 115 pounds in the latter part of the trip should be noted, on Plate XIII. The generator voltage at the start of the trip was maintained high at a value of 125 volts, very likely to produce a good showing while standing in the depot before leaving. This during the night was allowed to fall off to 104 volts minimum.

The steam consumption curve is seen to follow the load curve very closely, it being however, higher at low loads than would be expected, due to the curve upward of the steam consumption per kilowatt-hour for low loads, as shown by the curve on Plate XIV.

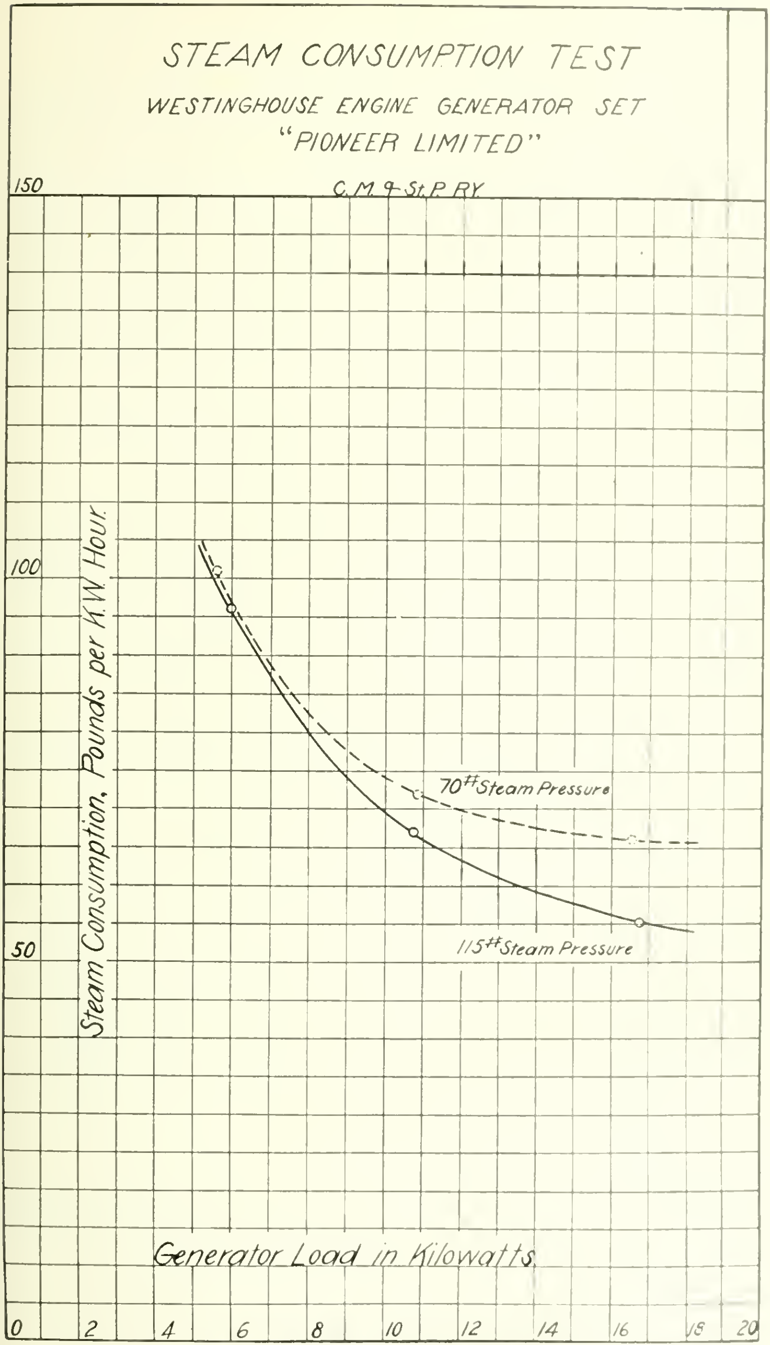

PLATE XIV.—STEAM CONSUMPTION TEST, WESTINGHOUSE ENGINE GENERATOR SET.

The relation between the curves of I. H. P. and E. H. P., Plate XIII, shows the mechanical and electrical efficiency of the set. In regard to the general operation of the equipment it must be said that at times the baggageman is too busy with his other duties to give the equipment proper attention, but in general the operation may be said to be satisfactory, the actual failure of lights being very infrequent, and at that time is generally due to the fact that the locomotive cannot provide enough steam.[3]

Test on Westinghouse Engine Generator Set

Northwestern Limited, C. & N. W. Ry.

This equipment is almost identical with those tested on the C., M. & St. P. Railway and Northern Pacific Railway, except that it has an auxiliary of Pintsch gas instead of storage batteries; and as there is only one engine change where this is required, this occurring in the middle of the night, the operation is satisfactory.

The equipment consists of a Standard Westinghouse engine, direct connected to a 17 K. W. generator operating at 400 R. P. M. and 110 volts.

The train equipment consists of the following:

Dynamo and Express Car, having..	8–12 c. p. lamps
Baggage Car, having	8–12 c. p. lamps
Compartment Sleeper, having	80– 8 c. p. lamps
Standard Sleeper, having	80– 8 c. p. lamps
Standard Sleeper, having	47–16 c. p. lamps
Dining Car, having	60– 8 c. p. lamps
Chair Car, having	36–12 c. p. lamps
Day Coach, having	22–16 c. p. lamps

Method of Test

The test on the road consisted in taking readings of current and voltage and steam pressure at fifteen minute intervals and

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[3] For the complete data of this test refer to the graduating thesis of J. I. Bush and H. L. Heller, University of Wisconsin, 1906.

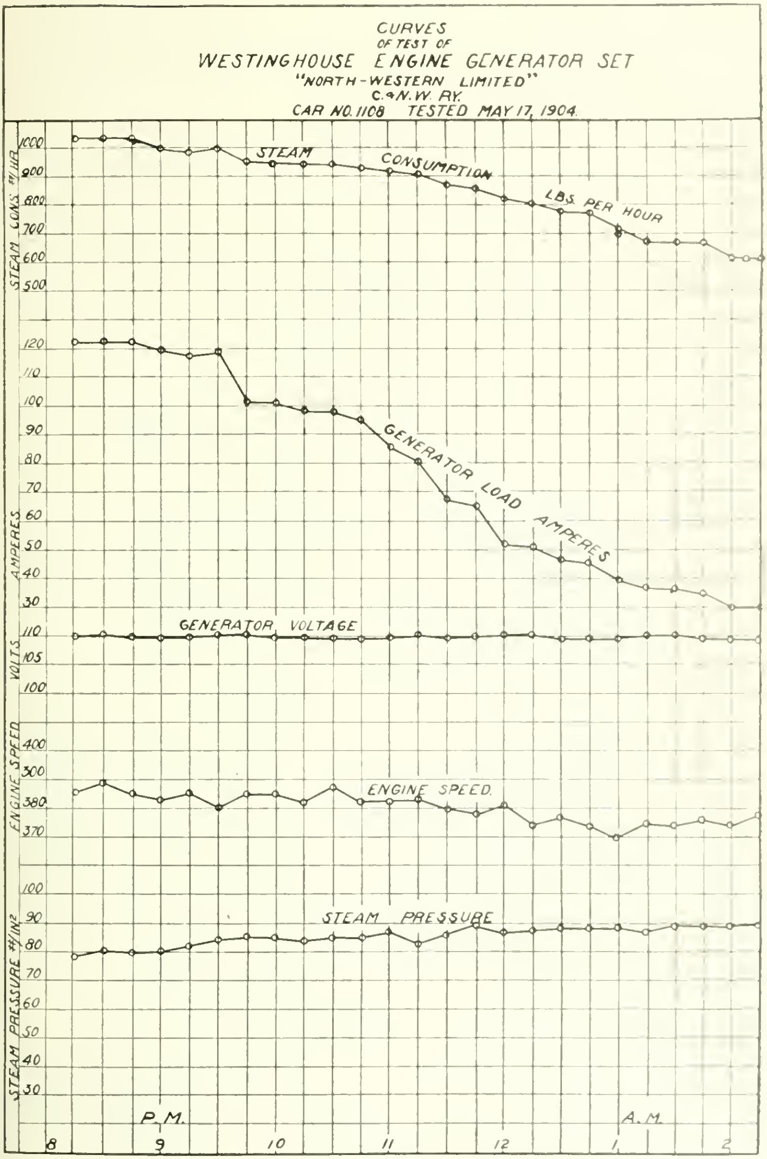

Plate XV.—Curves of Test of Westinghouse Engine Generator Set, C. & N. W. Ry.

indicator cards and speed readings every ten minutes. The engine was indicated by a special link mechanism fastened to the end of the shaft very similar to that used on the Northern Pacific test.

A steam consumption test was made in the yards at Chicago in which the steam consumption was measured, keeping the steam pressure constant at 90 pounds per square inch and varying the load. Steam was condensed in a surface condenser and collected in tubs and weighed on platform scales. Each reading extend over a period of twenty minutes.

RESULT OF TEST

Trip from Chicago to St. Paul—Car No. 1108

Total duration of test	5¾	hours
Average load	8.2	K. W.
Average steam pressure	86	lbs. per sq. in.
Average steam consumed	870	lbs. per hour
Average steam per K. W. hour	106	lbs. per K. W. hour
Total steam consumed on test	5000	lbs.

DISCUSSION OF RESULTS

By reference to Plates XV and XVI the complete results of the test are graphically observed. It is noted from Plate XV that the steam pressure, speed and generator voltage are practically constant, and that the load decreases during the night from 122 amperes at 8:15 to 30 amperes at 2:15, when the lights were cut off.[4]

TEST ON CONSOLIDATED AXLE EQUIPMENT

NORTHERN PACIFIC RAILWAY

The axle driven equipment of the Consolidated, Kennedy type, consists essentially of a generator, pole changer, battery, regulator, automatic switch, and wiring and switches within the car.

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[4] For complete data of this test refer to the graduating thesis of C. S. Peters, University of Wisconsin, 1904.

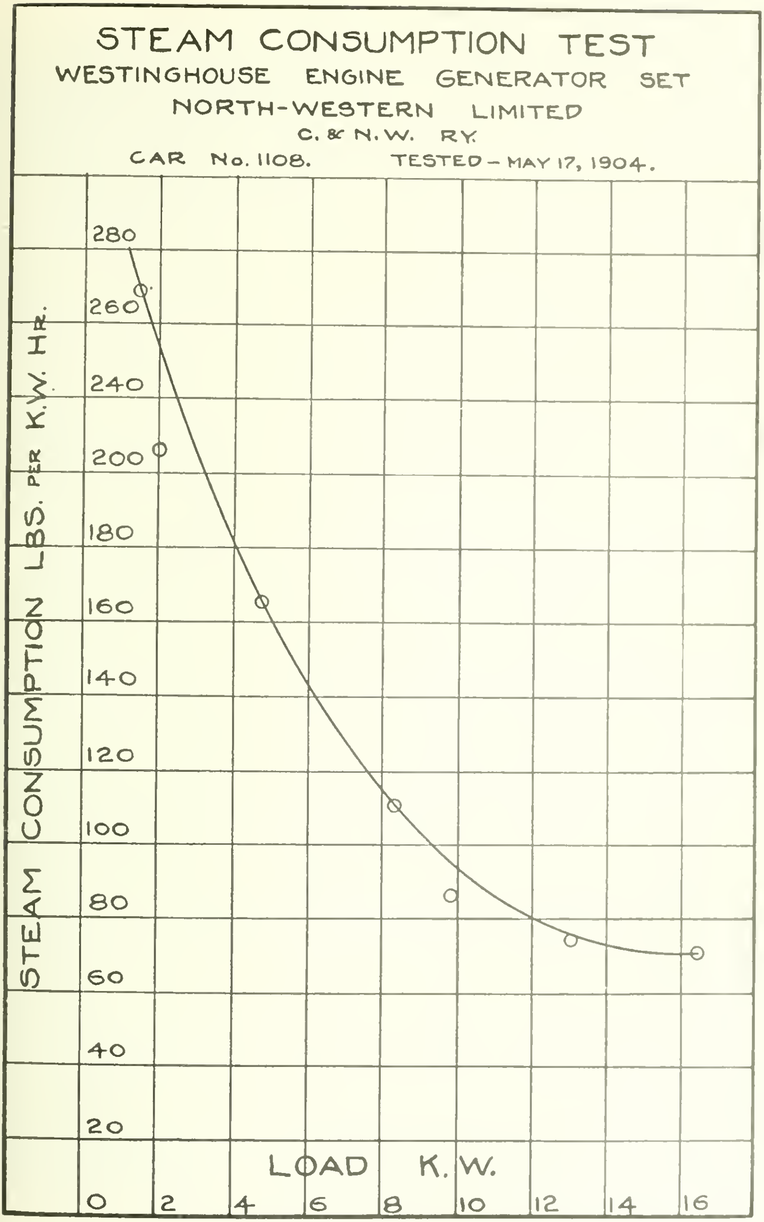

Plate XVI.—Steam Consumption Test, Westinghouse Engine Generator Set, C. & N. W. Ry.

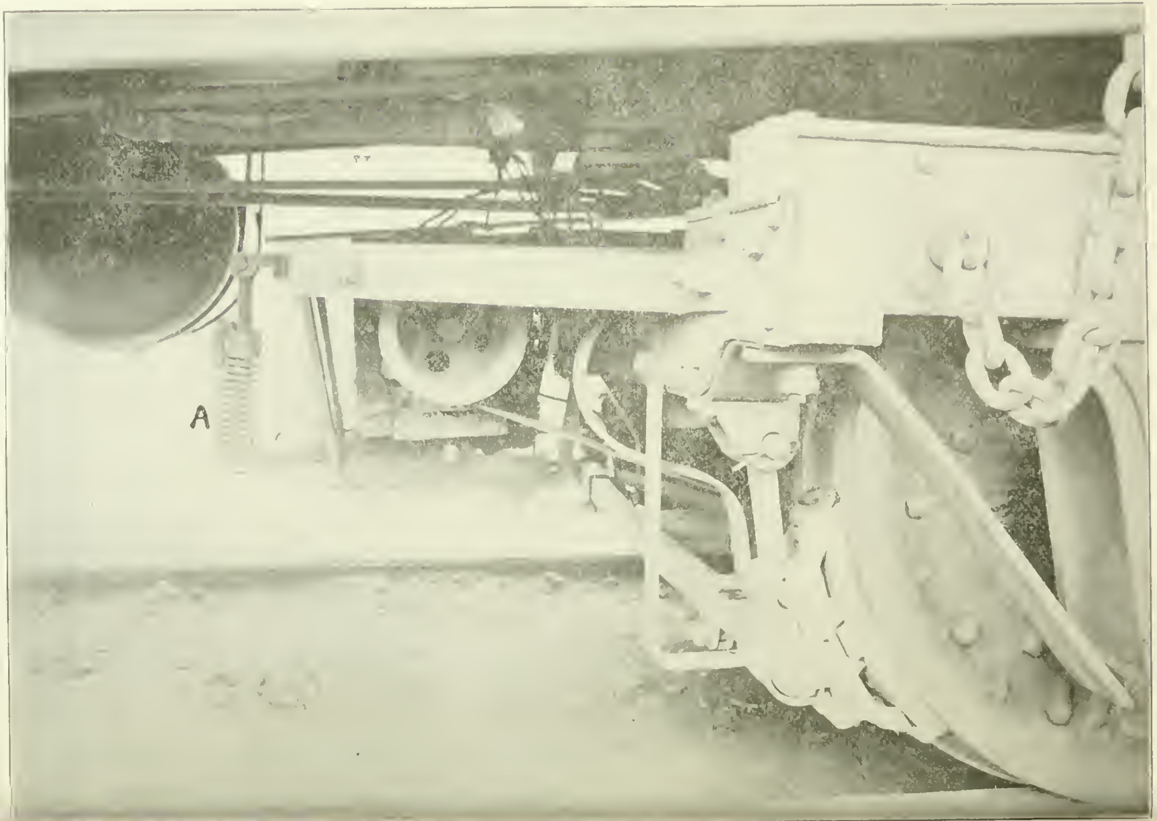

Plate XVII.—Showing Suspension of Generator on Consolidated

The generator is of bipolar, simple shunt-wound type and is provided with self-oiling bearings. It is encased in a dust-proof wrought iron casing which is provided with suitable covers and hand holes for repairs and inspection, and is suspended by irons bolted to the outer face of the forward truck sill (see Plate XVII) and pivoted on a rocker roller, a heavy adjustable spring, A, maintaining proper belt tension. The generator is belted to a large axle pulley ($20\frac{1}{2}$ inches in diameter) bolted to the axle. These pulleys are perforated to allow the sand and cinders to fall away from the belt surface. The generator field pieces are supplied with a few sheets of hard steel to insure proper polarity in the fields.

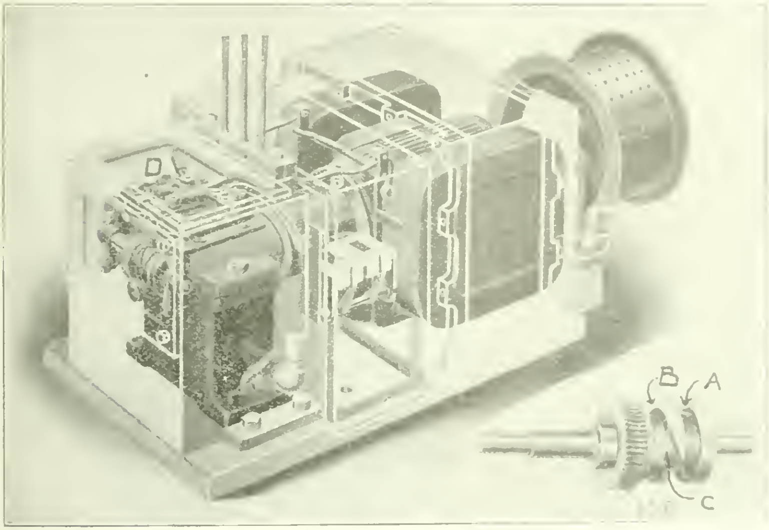

Plate XVIII.—Generator of Consolidated Axle Equipment.

The *pole changer* is that part of the appartus which maintains proper polarity in the circuit irrespective of the direction of motion of the car. This consists of a worm fitted on the armature shaft engaging with a worm-wheel on which is mounted a cam of peculiar construction, such that if the car motion be forward the cam follower will run continually in the slot A, but if the direction of motion be reversed the follower will be forced through the diagonal slot C into the slot B, where it will remain as long as the direction of car motion is the same.

As the cam follower is forced from slot A to slot B it causes a reversing switch at D to be thrown, thus maintaining proper polarity in the external circuit. This is obviously essential to the operation of the equipment, for if the generator were thrown on the line with wrong polarity it would cause an immediate short circuit of both generator and battery.

The *battery* comprises 16 cells each of 240 ampere hour capacity of the type 13-E of the Electric Storage Battery Co., and is located under the car. The battery is connected in parallel with the generator and line, serving to act as an auxiliary in maintaining the lights lit while the generator is inoperative. The subject of batteries as applied to train lighting is discussed in a separate chapter in this report, so the subject will not be considered further at this point.

KENNEDY REGULATOR

The regulator is an important part of this equipment from a technical point of view. It is shown on Plates XIX and XX and the details of the wiring on Plate XXI.

The principle on which the regulator is based is that of generator control by variable field resistance and lamp voltage control by means of a variable resistance in the lamp circuit.

The generator control is effected by means of the pair of solenoids A. A. B. B. (Plate XX) in which there is a floating plunger which operates the pair of cam followers C on opposite sides of the cam E.[5]

When regulation is necessary, one of the followers C is drawn up against cam E and this cam being driven by a motor with worm-wheel connection to the shaft G, drives the follower and causes it to turn one of the pair of rachet wheels R, Plate XIX, operating the field resistance inside of H.

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[5] A similar cam and pair of followers are located under the coils A, A as is shown under coils D, D.

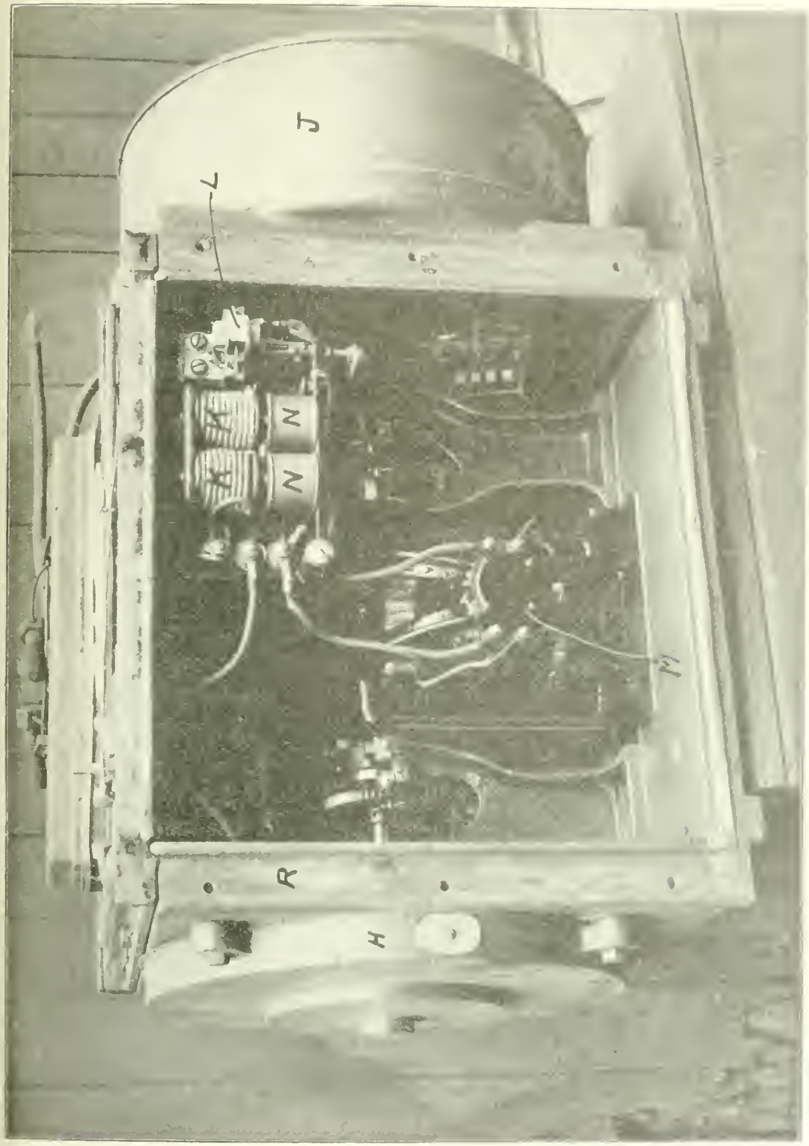

PLATE XIX.—KENNEDY REGULATOR

The controlling solenoid includes a double set of windings, those A, A, in the main generator circuit and those B, B, placed in the lamp circuit, being connected so that the magnetism of coils B, B, is in opposition to that of coils A, A. This allows the generator current to be increased when the lights are turned on, thus permitting the batteries to be charged somewhat at night and still not have the day charging rate be excessively high.

The lamp voltage control is effected by means of the pair of solenoids D, D, Plate XX, which are wound with fine wire and placed across the terminals of the lamp circuit. The mechanical operations are identical with those of the generator current controlling devices, the floating plunger governing the operation of the large rheostat, J, which contains the lamp circuit rheostat. This regulator has the distinction of being the only one in which the lamp regulation is entirely independent of the condition of the batteries as well as the number of lamps in use; but it is dependent upon the operation of several moving parts as well as the proper adjustment of the spring, S, for its successful operation.

The *automatic switch* is that part of the equipment which connects the generator with the lights and battery when its voltage has risen so that it is slightly above the battery voltage. It is shown in Plate XIX. The coils N, N are mounted on a movable arm pivoted at T on which is supported the lower contact point of the switch, L. These coils N, N are wound with fine wire and placed across the terminals of the generator so that when the generator voltage rises to slightly above that of the battery the magnetism developed in these coils will draw up the movable arm and close the contact at L. The coils K, K are wound with coarse wire and are placed in the main circuit of the generator so that as soon as the switch is closed at L the current flowing through these coils will immediately intensify the magnetism of the coils N and insure good contact at the switch.

These series coils have also a function in opening the automatic switch at the proper time. As the generator voltage falls on decrease of train speed, till its voltage is below that of the

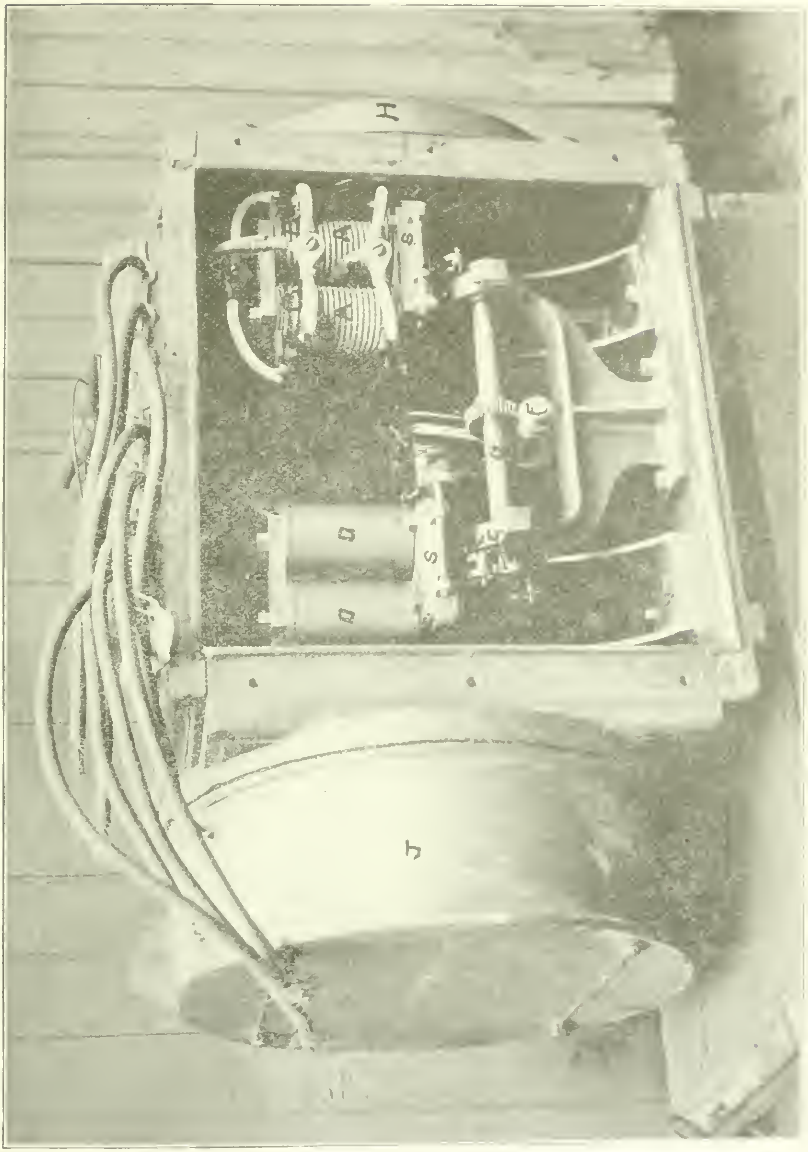

Plate XX.—Kennedy Regulator

battery, a reverse current will flow through the coils K, K, creating a magnetic flux in opposition to that of the coils N, N, so that the opening of switch will be actually accelerated by the repulsion of the coils.

METHOD OF TESTING

The problem of testing such an apparatus in actual operation on a railway train is a peculiarly difficult one. In the first place everything in the system is in continual fluctuation, the speed of a railway train is well known to be an extremely variable factor, and it may be said that everything in the system fluctuates with train speed, though in justice to the manufacturers of the equipment it must be said that the limits of fluctuation of generator pressure and current for change in speed are small. In addition to this the generator is alternately thrown off and on to the circuit at every stop and start, the lights being fed at one minute from the generator and another from the battery, so that the equipment presents a rather chaotic condition to one endeavoring to obtain a comprehensive set of results.

It was decided to take two different kinds of data, one of which might be called *Detail Data,* which consider the detail operation of the equipment and include those data which when plotted in curves show the relation between train speed, generator voltage, lamp voltage, battery voltage, field voltage, generator current, lamp current, battery current and field current; and the other of which consists of *Wattmeter Data,* including the total generator output, total consumption of energy by the lamps, total energy of battery charge and total energy of battery discharge, over the entire trip.

In order to facilitate taking the data a switchboard was constructed as shown in Plate XXI, which made it possible to take the whole set of readings within the time of ten seconds. This switchboard contained all the numerous switches and instruments used in making the test as shown by Plate XXI, and was placed in a double seat at that end of the car in which the regulator was located.

In wiring to the regulator, heavy insulated copper cables were

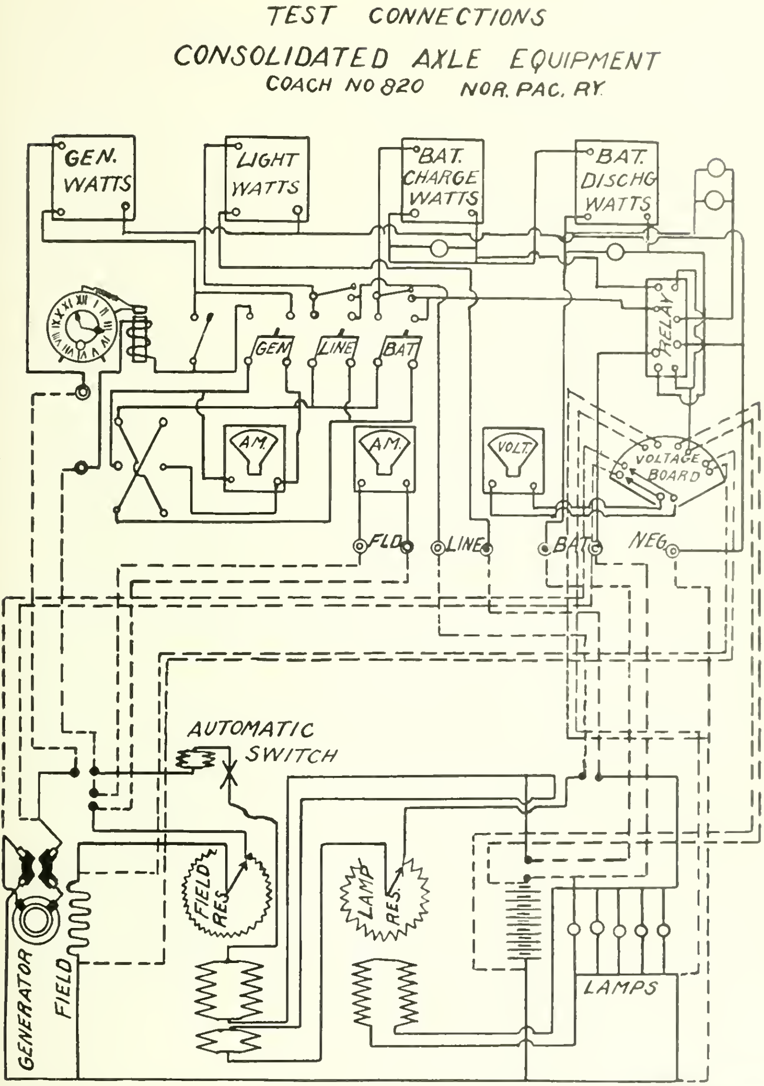

Plate XXI.—Test Connections, Consolidated Axle Equipment, Nor. Pac. Ry.

used corresponding to a No. 0, B. & S. gauge, so that the loss in test connections would be a minimum; these wires being passed under the seat and through a thin partition to the regulator closet.

The *test connections* are shown in Plate XXI. The lower half of the plate indicates the wiring connections of the axle equipment, while the upper half shows the test instruments and their connections. the dotted lines indicating the connections between the instruments and the axle equipment. The heavy dotted lines indicate No. 0, B. & S. gauge, while the fine dotted lines indicate voltage leads.

The reasons for taking the wattmeter data are obvious. The relation between the readings of the battery charge and discharge meters is of vital importance to the life of the battery, and the relation between the readings of the lamp and generator meters shows the total operating efficiency of the equipment. The meters employed were of the common integrating type, calibrated to the low voltage of this equipment.

The separation of the energy of battery charge from the energy of discharge presented a complex problem, as the current flows into the battery while the train is running and out of the battery while the train is stopped and lights are on. To separate these two values of energy, a polarized relay was constructed as illustrated in Plate XXII, to control the circuit relations of two wattmeters, one of which recorded the energy of battery charging and the other recorded the energy of discharging.

This polarized relay consists essentially of a heavy yoke of soft iron, A, (see Plate XXII, wound with about 40 turns of No. 4 insulated copper wire through which the total battery current passes, thus creating one polarity while the battery is charging and the reverse polarity while the battery is discharging.

Suspended between the pole pieces of this yoke is one end of an electro-magnet, B, of constant polarity. It consists of a small strip of soft iron wound with 400 turns of No. 20 insulated copper wire. This coil is placed in series with two lamps directly across the battery, so that a constant magnetic flux is obtained.

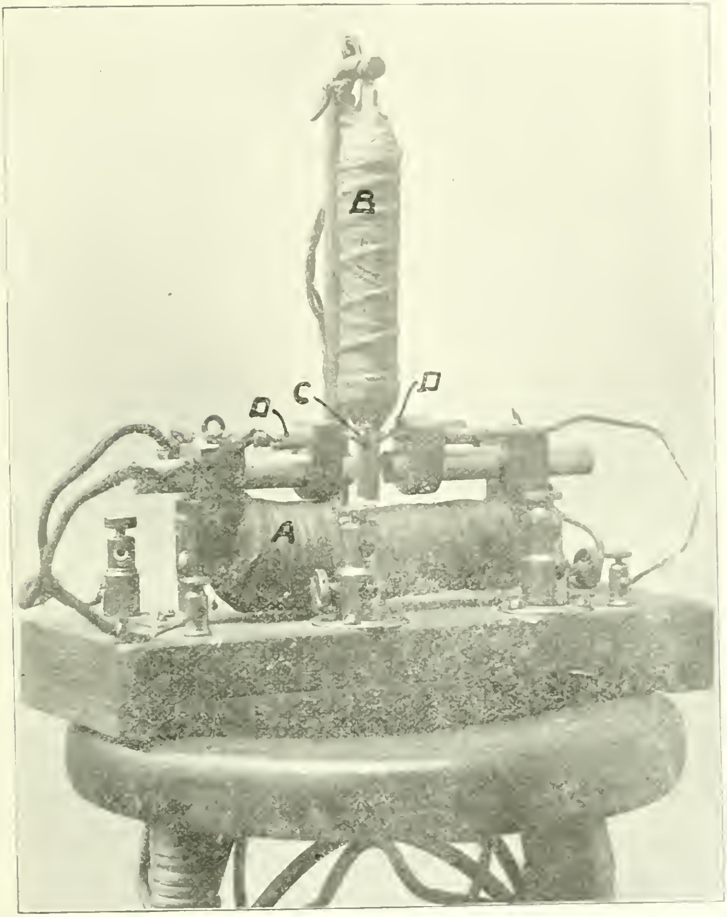

Plate XXII.—Polarized Relay.

Fitted on either side of this swinging bar of iron is an insulated brass button, C. When the battery current flows in, say, a charging direction, the reaction between the magnetism of the yoke and that of the swinging magnet draws the latter over till the brass button, C, makes contact between the two adjustable points DD, thus completing the circuit through the voltage coil of the wattmeter registering battery charge. The current coils of both wattmeters are placed in series with the heavy coil of the relay so that all battery current must pass through all three coils.

On reversal of the battery current, the polarity of the heavy yoke becomes reversed and the swinging magnet is drawn over to the other pole of the yoke, where the brass button on the other side of the swinging bar makes contact between the two contact points DD there located, thus completing the circuit through the voltage coil of the discharge wattmeter and causing it to record, the other wattmeter now being inoperative.

There are two pilot lights in the switchboard equipment, (see Plate XXI), which indicate when the corresponding wattmeter is operative, thus indicating whether or not the relay is working properly.

The other variable factor which it was necessary to determine was the total time of generator operation. A clock was fitted up on the principle of a stop watch operated by an electro-magnet in the generator circuit, as illustrated in Plate XXI. Obviously when the generator current flows through the solenoid, the keeper will be drawn down, thus stopping the clock, and when the generator is cut out of the circuit, the keeper will be pulled up by a spring and start the clock again, thus the clock records the time the generator is inoperative.

The *train speed* was determined by counting the rail clicks, since in case of a 30 foot rail the number of clicks in 20½ seconds gives directly the speed of the train in miles per hour. In case of 33 foot rails the clicks were counted for 22½ seconds, time being taken with a stop watch. This was found to be a very simple and sufficiently accurate method of taking speed readings.

Generator Efficiency. On arriving at St. Paul, a stray power test of the generator was made by the rated motor method. The belt was removed from the generator and the generator was driven at various speeds with no load on the armature, by means of a small motor the losses of which had been previously measured. The input of the motor was then measured while driving the unloaded generator at various speeds and various excitations, from which the power necessary to supply these generator losses can be computed.

Knowing the stray power losses and armature resistance of the generator, the power absorbed from the driving belt or gearing by the generator while delivering any load to the lighting equipment can be computed; from which efficiency curves follow:

IMPORTANT RESULTS OF TEST

Total Time of Test	31 Hrs.
Generator Operating	23 ½ Hrs.
Generator Not Operating	7 ½ Hrs.
Lamps Lighted	13 ½ Hrs.
Total Generator Output	28.6 K. W. Hrs.
Total Lamp Consumption	14.6 K. W. Hrs.
Total Battery Charge	12.2 K. W. Hrs.
Total Battery Discharge	4.7 K. W. Hrs.
Average Generator Efficiency	80 %
Average Belt Efficiency (assumed)	97 %
Average Power absorbed from axle	2.08 H. P.

Total Efficiency for the Run —

$$\frac{\text{Lamp Cons. x Gen. Eff. x Belt Eff.}}{\text{Gen. Output}} = 39.6\ \%$$

DISCUSSION OF TEST

It was originally planned to make this test extend over the complete round trip of the car from St. Paul to Portland, Ore., and return, but the pole changer on the generator which was used, failed to work properly in the early part of the trip and was not repaired till the second day of the return trip, from which time the test was started.

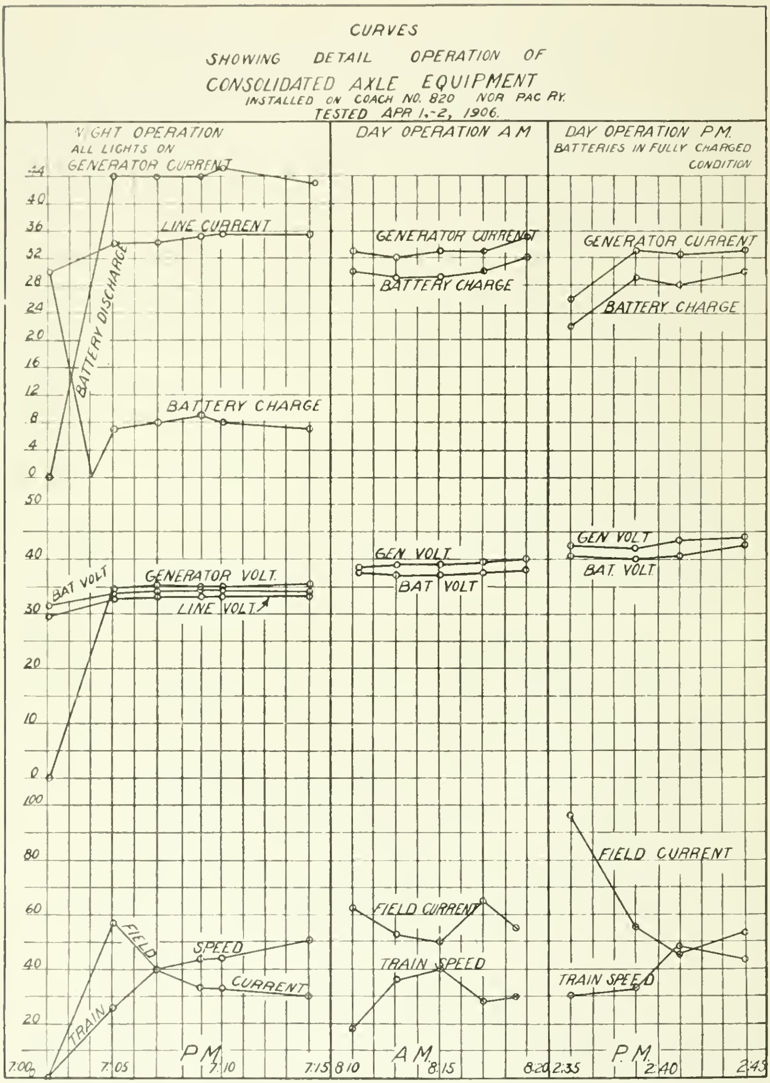

Plate XXIII.—Curves Showing Detail Operation of Consolidated Axle Equipment, Nor. Pac. Ry.

It is not within the limits of this work to present in detail all the great mass of data taken in this test and accordingly only such data have been selected as are needed to typically illustrate the operation of this equipment, and these are plotted in the accompanying curves on Plates XXVIII and XXIV.

Referring to the tables of results on page 65, special attention should be called to the fact that the batteries are excessively overcharged, the ratio being 4.7 K. W. Hr. discharge and 12.2 K. W. Hr. charge during 13½ hrs. of night run and 17½ hrs. of day run. This might be remedied by changing the regulator setting so as to reduce the generator current by about five amperes, which would have given about 9.4 K. W. Hr. charge with the 4.7 K. W. Hr. discharge. This amount of charging would doubtless be ample to care for battery efficiency and also to make recovery from any heavy discharges due to delays of the train.

This setting of the regulator would give a generator output of 39 amperes when all lights are on instead of the 44 amperes of the test. (See Plate XXIII.)

The excessive overcharge of the batteries is shown plainly by the voltage readings of the battery taken throughout the day, plotted on Plate XXIV. It is seen that by 12:30 P. M. the voltage had risen to its maximum of about 42 volts indicating charged condition of the battery and it remained at that value throughout all the rest of the charging period, which continues all afternoon and till the lights are turned on at 6:30 P. M.

Such excessive overcharging causes rapid destruction of the battery plates and should be prevented.

Referring to the curves on Plate XXIII it is to be noted:

1. During night operation the generator charges the batteries with about 8 amperes as well as lighting the lights.

2. Field current varies inversely with the train speed.

3. Lamp regulation is fair, holding the lamp voltage between 29 to 33 volts but not so good as was expected from the special lamp regulator installed on this equipment.

4. Generator current regulation is fairly constant for wide variations of train speed.

Referring to the day operation in the second and third columns of this same plate, it is noted:

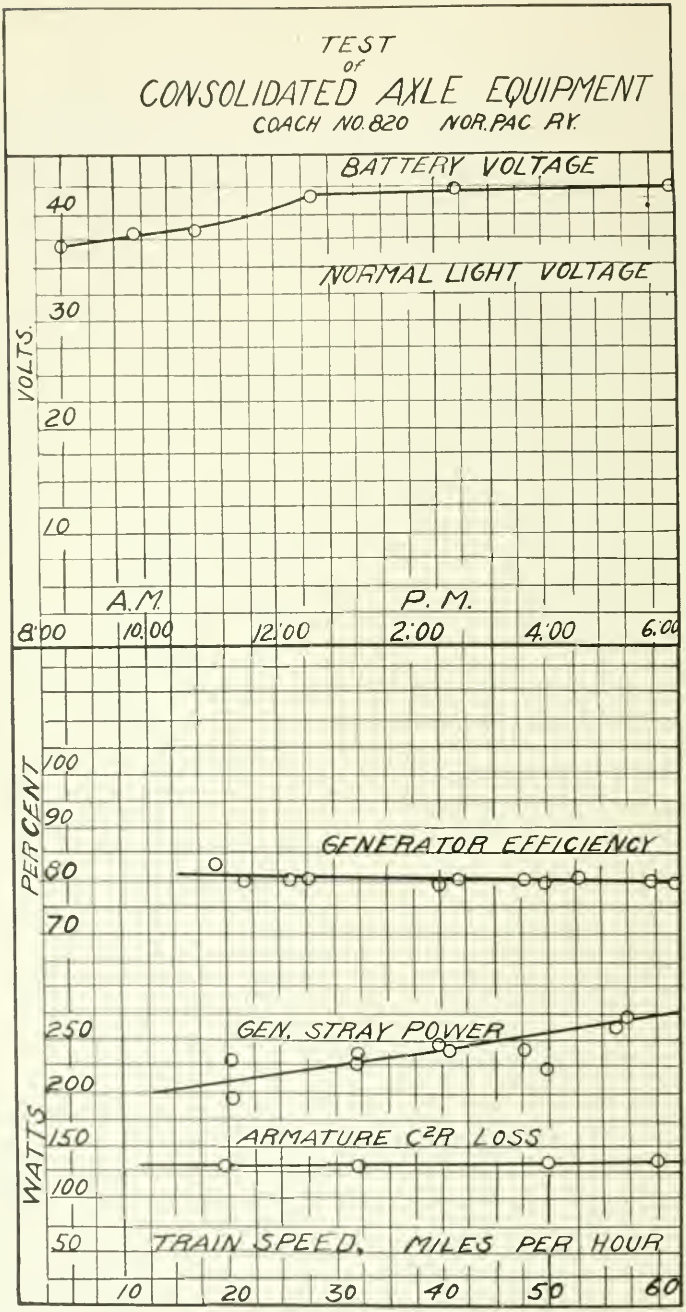

Plate XXIV.—Showing Generator Losses and Efficiency and Illustrating the Battery Overcharge.

1. Generator current has dropped to 33 amperes but stays practically constant at that point for both A. M. and P. M.

2. Generator voltage rises directly with the battery voltage, proving the point that the equipment regulates for constant current output irrespective of the voltage required.

A voltmeter test of the regulation afforded by this equipment was made on a later run, after the regulator had been carefully adjusted but the variation of voltage remained about 10 per cent.[6]

TEST OF CONSOLIDATED AXLE EQUIPMENT

OBSERVATION CAR "DYNAMENE,"

C., B. & Q. RY.

This equipment is one made by the Consolidated Company at an earlier date, and the Kennedy regulator as described on page 56 was developed as an improvement over this type.

This equipment has substantially the same principles of control as the Kennedy regulator previously described, except in regard to regulation of lamp voltage.

It consists essentially of a generator, pole changer, automatic switch, regulator, storage battery auxiliary, and lamps and switches within the car.

The generator and pole changer are identical with those described on page 55 and will not be considered further at this point.

The regulator consists essentially of a large controlling solenoid A (See Plate XXVI), an automatic switch C operated by the electro-magnets B and D, an operating motor E, a field rheostat the contact points of which are shown at R, and a lamp circuit rheostat at M.

As the train speed reaches the value at which the generator voltage is equal to that of the battery, the magnetism created

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[6] For complete data of this test refer to the graduating thesis of O. B. Cade and A. J. Walsh, University of Wisconsin, 1906.

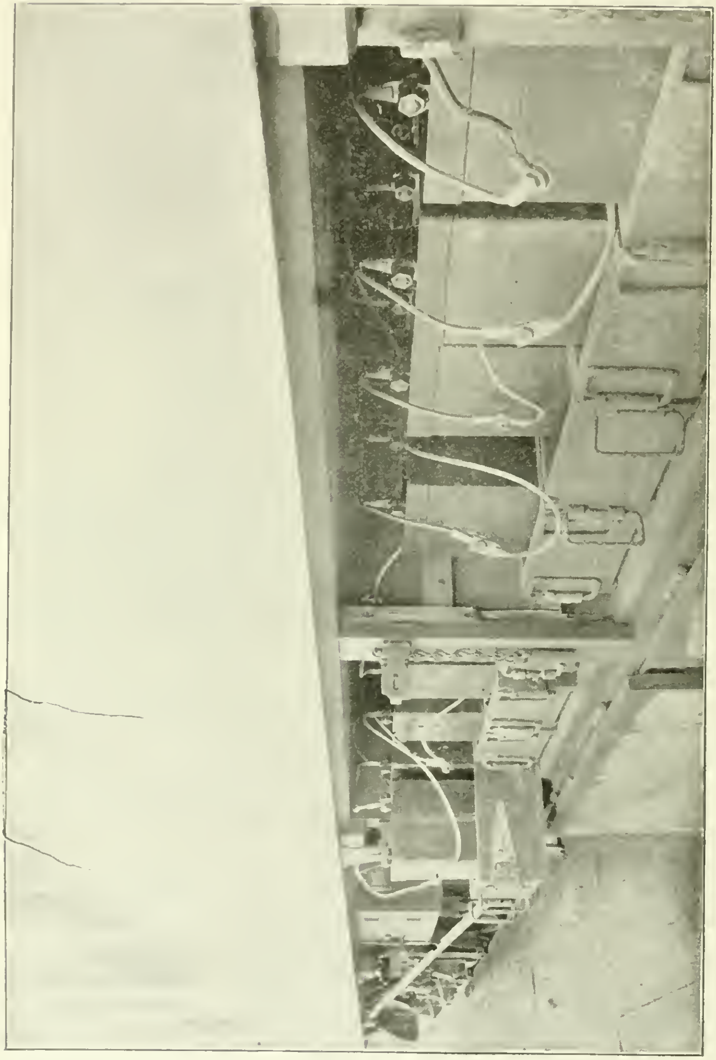

PLATE XXV.—SHOWING LOCATION OF BATTERY.

in the two shunt coils D, which are mounted on a movable arm, will be such as to draw themselves up to the magnet coils B, thus closing the switch C connecting the generator in parallel with the battery and lights.

As the generator speed becomes higher, its voltage tends to rise above that of the batteries and the generator assumes its load. The generator current flowing through the large solenoid A then affects an iron plunger J in direct proportion to current flowing, this magnetic pull being counterbalanced by an adjustable spring K, the adjustment of which determines the value of the normal generator current.

The motion of this magnetically controlled plunger is transferred by the lever arms O to the control of two little ratchet dogs P which are being moved back and forth continually by an eccentric on the motor worm-wheel F. These little ratchet dogs engage with two ratchet wheels, one of which is right handed and the other of which is left handed, shown at O in Plate XXVI, these wheels being mounted rigidly on the adjustable field rheostat arm R. When regulation of the voltage is necessary, one of the ratchet dogs P is allowed to engage with its corresponding ratchet wheel G and cause it to be rotated, moving the field rheostat arm R to such a point as to produce the desired voltage. It is obvious that only one of these motor driven dogs is allowed to engage with its corresponding wheel at one time.

A rheostat at M is inserted in the lamp circuit when the generator becomes operative, to compensate for the difference between battery charging voltage and battery discharging voltage, thus maintaining a reasonably constant voltage on the lamps. This is effected by the rheostat arm and resistence contact points at M being operated by a cam and follower mounted on the ratchet wheel G of such construction that it causes the resistance to be all inserted at the first quarter turn of the ratchet wheel.

In regard to the operation of the automatic switch (B, C, D), after the magnetism of the generator shunt coils becomes of sufficient intensity in the coils DD, they draw themselves up to the coils BB, thereby closing the generator switch C. The coils

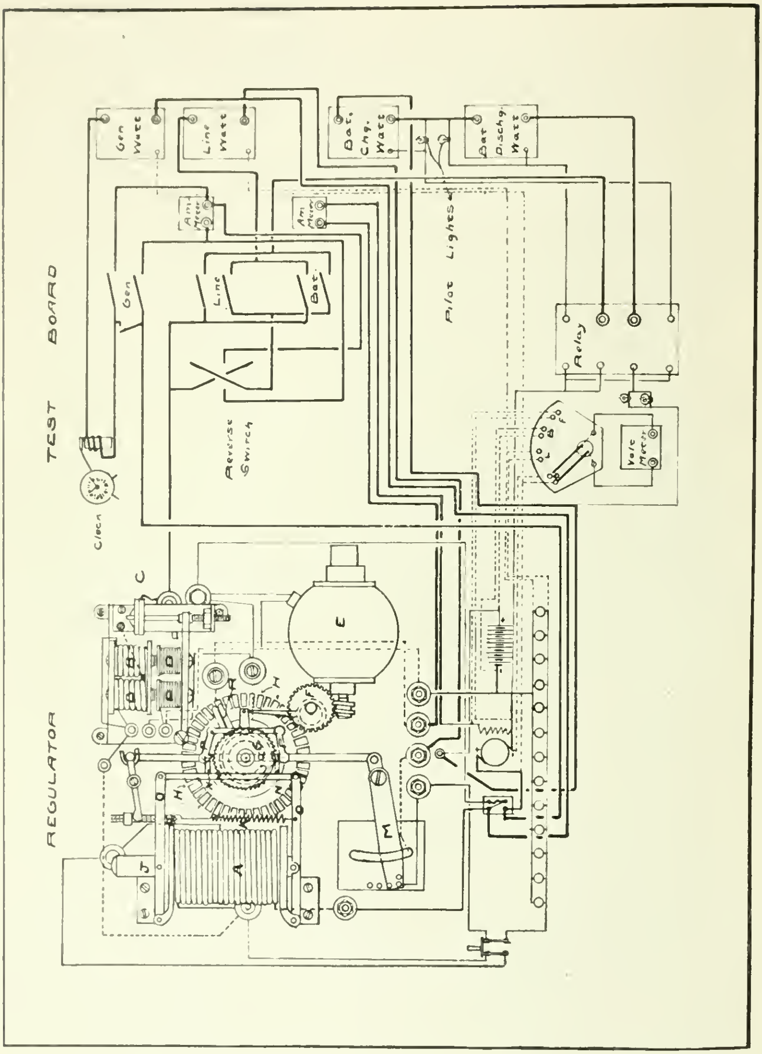

PLATE XXVI.—REGULATOR (OLD TYPE) OF CONSOLIDATED AXLE EQUIPMENT.

BB are wound with heavy wire and all the generator current passes through them so that on closing the generator switch C the generator current flowing through them will intensify the magnetism of coils DD, and insure good contact at C.

The *battery* consists of a set of 16–240 ampere hour cells of the type 13–E, made by the Electric Storage Battery Co., which are located beneath the car as illustrated in Plate XXV. The jars used are of reinforced hard rubber and are set in wooden trays, two jars in a tray.

METHOD OF TEST

The method of making the test was almost identical with that used in the previous tests and described on page 60. Several changes, however, were necessary in making test connections, (as shown by Plate XXVI).

The car upon which the equipment was operating was a Pullman sleeper and observation car, so there was no accommodating space in which to lay any bulky switchboard as in previous tests. The four wattmeters (shown in Plate XXVI) were placed on the platform over the steps in the vestibule, and the remainder of the test apparatus was located within the regulator locker.

The generator was identical with that tested on the Northern Pacific Ry. so a duplicate efficiency test was not made, but reference can be made to the curve on Plate XXIV in connection with this test. The efficiency itself is slightly different due to the difference in output.

IMPORTANT RESULTS OF TEST

Farnsworth Consolidated Axle Equipment on Observation Car Dynamene—Chicago to Kansas City.

Total time of trip	14 hrs. 10 min.
Total time Generator operating	11 hrs. 35 min.
Total time Generator not operating	2 hrs. 35 min.
Total time Stops	1 hrs. 22 min.
Total time Generator running dead	1 hrs. 13 min.
Total time Lights on Batteries	2 hrs. 35 min.

Total Generator Output	19.6 K. W. Hr.
Total Lamp Consumption	8.38 K. W. Hr.
Total Battery Charge	7.9 K. W. Hr.
Total Battery Discharge	1.86 K. W. Hr.

Kansas City to Chicago.

Total time of trip	13 hrs. 42 min.
Total time Generator operating	10 hrs. 55 min.
Total time Generator not operating	2 hrs. 47 min.
Total time of stops	1 hrs. 24 min.
Total time Generator running dead	1 hrs. 23 min.
Total time Lights on Batteries	2 hrs. 47 min.
Total Generator Output	19.2 K. W. Hr.
Total Lamp Consumption	7.28 K. W. Hr.
Total Battery Charge	7.03 K. W. Hr.
Total Battery Discharge	1.87 K. W. Hr.

Above readings are corrected for loss in test connections.

Average Generator Eff. = 80%.

Total Efficiency of Equipment—Kansas City to Chicago =

$$\frac{\text{Lamp Cons. x Gen. Eff. x Belt Eff.}}{\text{Gen. Output}} = 29.5\%$$

The average battery discharge equals 1.86 K. W. Hr.

In order to compensate for battery efficiency of 50%, there should have been 3.7 K. W. Hr. charge. Instead of this it is seen that there was about 7.5 K. W. Hr. (av. of two trips). This leaves 3.8 K. W. Hr. of destructive overcharge which might be eliminated.

3.8 K. W. Hr. at 40 volts = 95. amp. hrs.

Since the generator was operating for about 11 hrs. this would represent an excess of 8.6 amperes in the regulator setting, and the generator might be set at about 33½ amperes with all lamps on instead of 42 amperes as at time of test.

DISCUSSION OF RESULTS

The most striking of the results observed, and one which is of critical importance to the life of the equipment, is that the batteries are tremendously overcharged on both outgoing and return trips, as is shown by a comparison of the values of energies of battery charge and battery discharge as shown on page 74. The cause of this is primarily due to the fact that the regulator was set too high, a fact which seems to be universally true in all constant current regulation. This is necessary to a certain degree to be on the "safe side" in maintaining the lights, but an extreme overcharge such as is here experienced should not be allowed as it is sure to cause the early destruction of the battery.

The results of this test again illustrate that objectionable part of axle operation which is inherent in the arrangements affording constant current regulation. It is noted from the description on page 71 that the iron plunger J which controls the operation of the field rheostat is held in equilibrium between the magnetic pull of the solenoid and the tension in the spring K. Now the magnetic pull of the coil A is proportional to the current flowing through that coil and is no function of the generator voltage so that the regulation will be such as will maintain constant current output of the generator irrespective of its voltage. This is a great disadvantage from a battery standpoint, in that after the batteries have become fully charged they still continue to be overcharged at the normal rate so long as the generator is operating.

Attention should be called to the fact that the total trip efficiency of the outfit is only 29.5%. This is due largely to the fact that the batteries are greatly overcharged, thus wasting a large amount of power, and it is also due to a large line loss, which is shown by the generator output being considerably higher than the sum of the lamp consumption + battery charge—battery discharge. This indicates a very high line loss and is substantiated by a reference to Plate XXVII which shows an average line loss of about 13%. The values given under wattmeter readings on page 74 have been duly corrected for the instrumental errors, so that the readings are true values. It should be noted that the voltage connections of the wattmeters were provided by special leads from the generator, line, and battery so that the readings are not vitiated by the line loss.

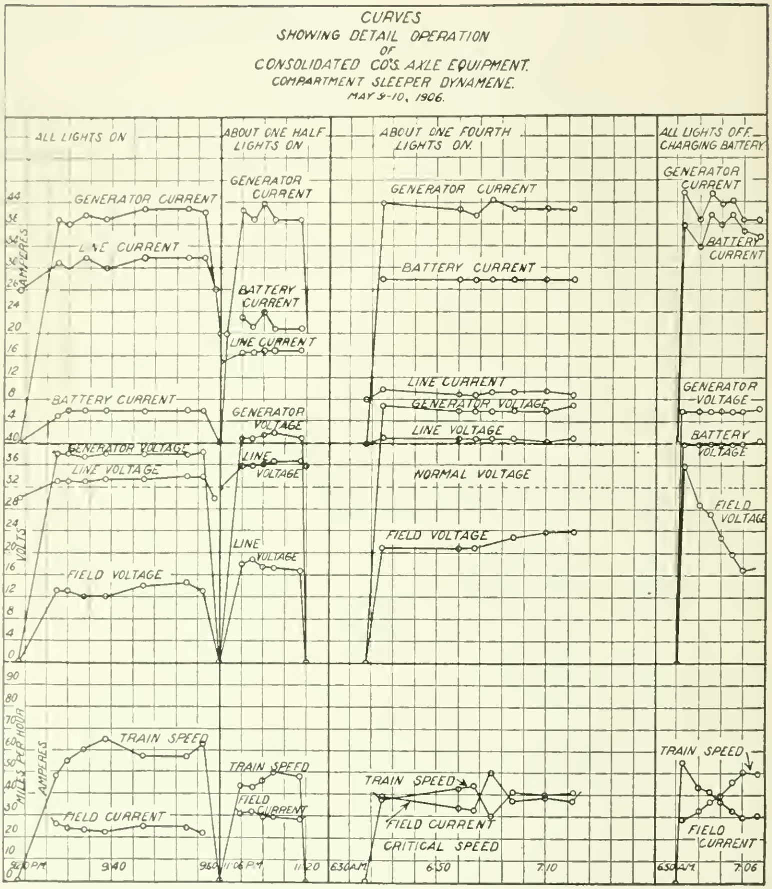

PLATE XXVII.—CURVES SHOWING DETAIL OPERATION OF CONSOLIDATED AXLE EQUIPMENT, COMPARTMENT SLEEPER DYNAMENE.

In discussion of the detail curves of operation, Plate XXVII, there are many important features to be noted which are typical in the operation of this equipment.

It should be first noted that these curves are in four different sets: one under full load condition of lighting, another with only half the lights on, a third with only one-fourth the lights burning and the fourth set of curves indicating the detail operation while charging batteries with no lights on.

The uppermost curve shows that the generator current remained practically constant at all times whether all lights are on, one-fourth lights on, or no lights on. This substantiates the statement that the regulator is one for constant current irrespective of the generator voltage.

Another point of particular interest in the curves is the variation in lamp voltage as the line current decreases and the batteries become charged. It is also noted that the lamp voltage varies directly with and is almost equal to the battery charging voltage, thus indicating the undesirability of this method of inserting the rheostat.

Another point of technical interest is shown by the two lower curves, in the inverse variation of field current and train speed, an increase in train speed being always accompanied by a decrease in field current and vice versa.[7]

TEST OF NEWBOLD AXLE EQUIPMENT

NORTHERN PACIFIC RY.

DESCRIPTION OF APPARATUS

The axle driven equipment of the Newbold type is based on essentially the same principles as certain earlier devices, the difference in design being of a mechanical nature largely. It is of the class that controls by varying field resistance.

The essential parts are, a generator belted to a large axle pulley, a storage battery to assume the load of lighting while the generator is inoperative, an automatic switch to close the

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[7] For the complete data of this test refer to the graduating thesis of A. P. Hoefer and Edgar Kearney, University of Wisconsin, 1906.

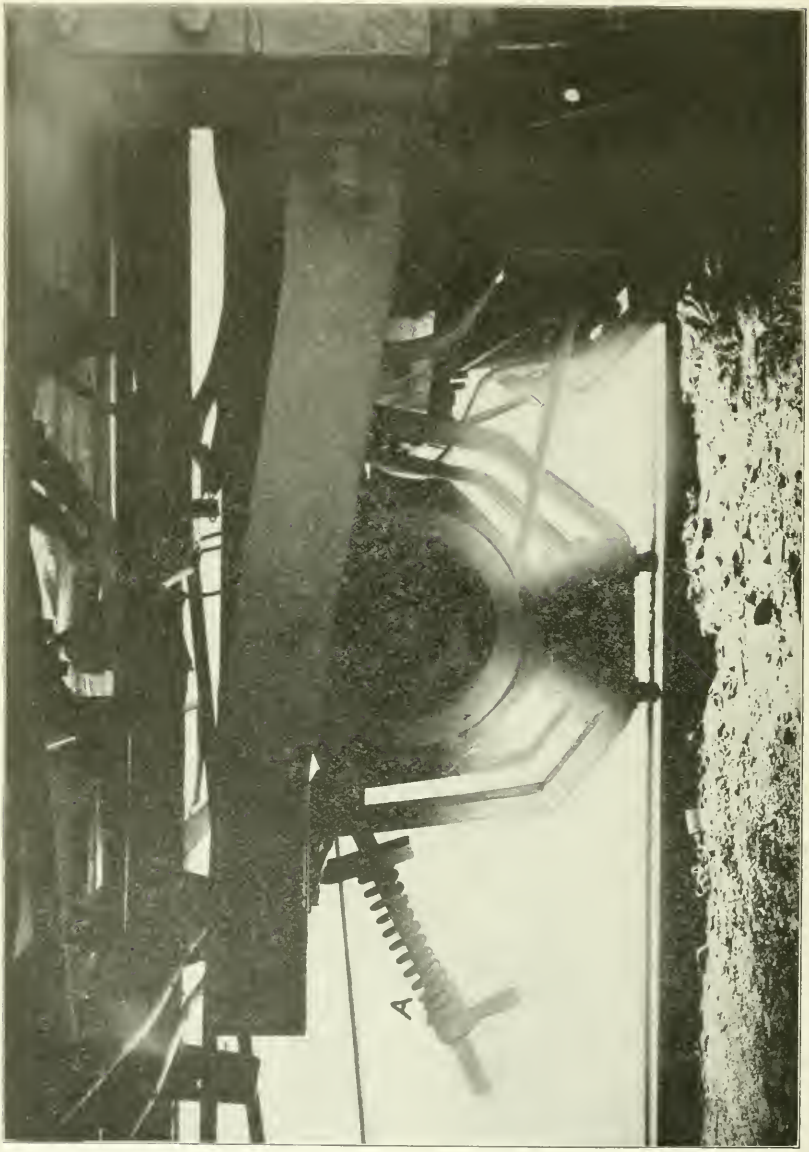

PLATE XXVIII.—GENERATOR OF NEWBOLD AXLE EQUIPMENT.

generator circuit when the critical speed is reached, a regulator to maintain the generator voltage constant by adjusting a suitable field rheostat, and a pole changer to provide proper polarity of the generator to the batteries independent of the direction of rotation of the generator.

The *generator* is of a 60 volt, 40 amp., 4 pole, direct current type. It is suspended from the outside of the front end of the truck sill, as per Plate XXVIII, and is pivoted on a rocker roller that is set on the supporting frame parallel to the car axle, thus allowing the adjustable spring A to maintain the proper belt tension. The belt is a 4 ply canvass rubber belt 4″ wide and passes over and under the truck sill as shown.

Oil rings and a quantity of oil sufficient for several months lubrication are supplied.

The generator is encased in a dust proof casing which is supplied with a single large hand hole which gives access to the brushes for repairs and inspection. This is provided with a felt lined cover which renders it dust proof. The case is built so that the end may be easily removed and the armature be readily taken out. The generator having four poles, the current is taken from the two adjacent brushes on the forward side of the commutator, thus making the brushes more accessible.

The *pole changer* is that part of the mechanism which provides proper polarity to the circuit whichever the direction of motion of the car may be. A worm is fastened to the armature shaft and engages a worm wheel. To this wheel is fastened a friction-strap clutch that grips a four-pole switch in case the motion of the train be reversed and drags it around till it makes contact in the reverse manner, then at this point a dog trips the friction-strap clutch and the worm wheel is allowed to turn thereafter without the friction of the clutch. On reversal of the motion of the car, the switch is reversed, thus keeping proper polarity in the circuit whatever the direction of train motion. A few sheets of hard steel are supplied in building up the pole pieces of the field magnets to insure proper magnetic polarity of the fields.

The function of the *automatic switch* is to close the generator

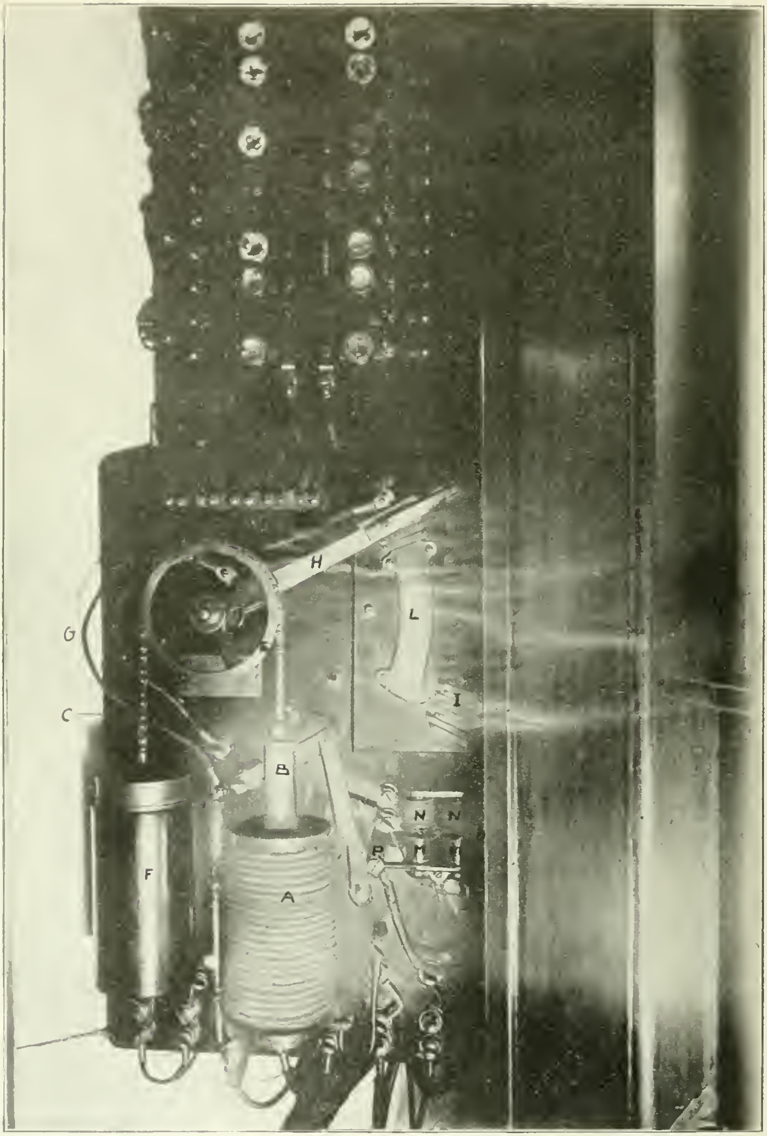

PLATE XXIX.—REGULATOR OF NEWBOLD AXLE EQUIPMENT.

circuit when the critical speed is attained. A coil of very fine wire, M, Plate, XXIX, is mounted on a lever arm pivoted at P, and is connected directly across the terminals of the generator, the adjustment being such that when the generator attains a voltage equal to that of the battery, the magnetism developed in this coil will be of sufficient strength to draw up the lever arm, thus closing the switch at O. When the generator, now on the line, begins to assume the load, all the current passes through the series coil N and increases the magnetic pull of the shunt coil M, insuring good contact in the automatic switch O.

In opening the automatic switch, the series coil has an important function which is not generally recognized. For simplicity in explanation of this, consider all lights off, *i. e.*, the generator furnishing current for charging battery in the day time. When the speed of the train is above the critical value the generator is charging the battery and the current passing through the series coil N intensifies the magnetic pull of the shunt coil M. Now if the speed decreases, the generator voltage drops till it is equal to that of the battery provided the speed decreases sufficiently and the current flowing will be zero, but still the automatic switch will stay closed due to the magnetic pull of the shunt coil M. But, now, as soon as the generator voltage drops a little below that of the battery there will be a current flow in the reverse direction through the series coil N, thus creating a magnetic flux in it in opposition to that of M which will accelerate the opening of the switch.

It is obvious that if the shunt coil alone were used to operate the automatic switch, the battery pressure would tend to hold it closed even far below the critical speed, since the battery, generator, and shunt coil are all in parallel when the switch is closed, and an injurious battery short-circuit would occur, or, if the automatic switch did open, it would do so under heavy arcing due to the battery discharge current.

The function of the *regulator* is to maintain proper voltage in the system. In this equipment it is properly called the "Gravity Regulator" as it depends on balancing the pull of gravity on a shot bucket on one side against the pull on an electric magnetic solenoid on the other. This is accomplished by the apparatus illustrated in Plate XXIX. The generator current energizes the large coil A which actuates the plunger B, this being suspended on a flexible chain C which passes over a wheel E mounted on ball bearings and fastened to the piston of the dashpot F. The piston of this dashpot is loaded with shot to an amount which is adjusted to balance the pull on the core of the rated generator current flowing through the coil A.

From this balancing wheel is extended a long arm H carrying two contact shoes, one of which carries the field current and engages with the bars I of the field rheostat and the other G, which carries the lamp current and makes contact with the corresponding bars of the lamp rheostat which are shown above L.

The lamp rheostat is so placed that its contact points are all cut into circuit when the lever arm first moves down. The function of this lamp rheostat is to compensate for the rise in voltage of the generator over that of the battery in assuming the load from the battery.

In regard to this dashpot piston loaded with shot,—there are two compartments to it, one loaded heavily with shot and one with no shot in it at all. These are so placed that when the arm H is in the zero position the heavier shot piston is not supported by the chain C but rests on the top edge of the dashpot F, so when the generator circuit is first closed a slight current in the coil A will overcome the weight of the lighter piston, thus drawing the plunger B into the coil A and causing the arm H to move downward until the lighter piston comes in contact with the heavy one above it, thereby cutting in all the resistance of the lamp rheostat and the first few sections of the field rheostat. Now, as the speed of the generator increases and the generator assumes more load, the magnetic pull of the solenoid A increases until it reaches a value sufficient to overbalance the weight of both pistons in the dashpot F, whereupon the arm H is drawn downward cutting in the field rheostat I as may be needed.

Another function of this dashpot is to render the operation of the plunger and lever arm rather sluggish. This is due to the fact that the dashpot piston is made to fit closely to its cylinder and on raising or lowering the piston, air is forced in or out of a tiny hole in the bottom of the cylinder. This is essential in protecting the equipment from accident and abuse, for if, due to some poor connection in the circuit the generator current should come and go, or if a blown main fuse should be replaced while running at a high speed, a great "hunting effect" would take place if the dashpot were omitted, that is, the generator voltage and current would surge up and down between wide limits, all due to the fact that the field magnets do not respond immediately to a change in field current.

The battery consists of a set of 32 cells of type 13-E of 240 ampere hour capacity, made by the Electric Storage Battery Co., located beneath the car in the same manner as shown in Plate XXV.

The fundamental principle at the basis of this regulator is that as the generator pressure tends to rise the battery current input rises almost proportionally to the *increase* in voltage. This energizes the coil A more strongly, thus pulling the plunger down farther and cutting in more field resistance I till normal conditions are restored and the generator current returns to normal value. On a decrease of speed occurring the reverse operation occurs, the lever arm H being gradually lifted by the weights in F overcoming the decreasing pull of the solenoid, till the pressure is raised to normal value, this continuing till the critical speed is reached, when, on a slight further decrease of speed, the automatic switch opens and the lights are fed from the battery.

METHOD OF TEST

The method of test was essentially the same as that described on page 60, but is illustrated more in detail by Plate XXX. The lower half of the plate indicates the equipment as normally installed, the upper half shows the testing instruments, while the dotted lines indicate the wiring between the instruments and the equipment, the heavy dotted lines indicating wire of No. O. B. & S. gauge, while the fine dotted lines indicate where voltage leads were used.

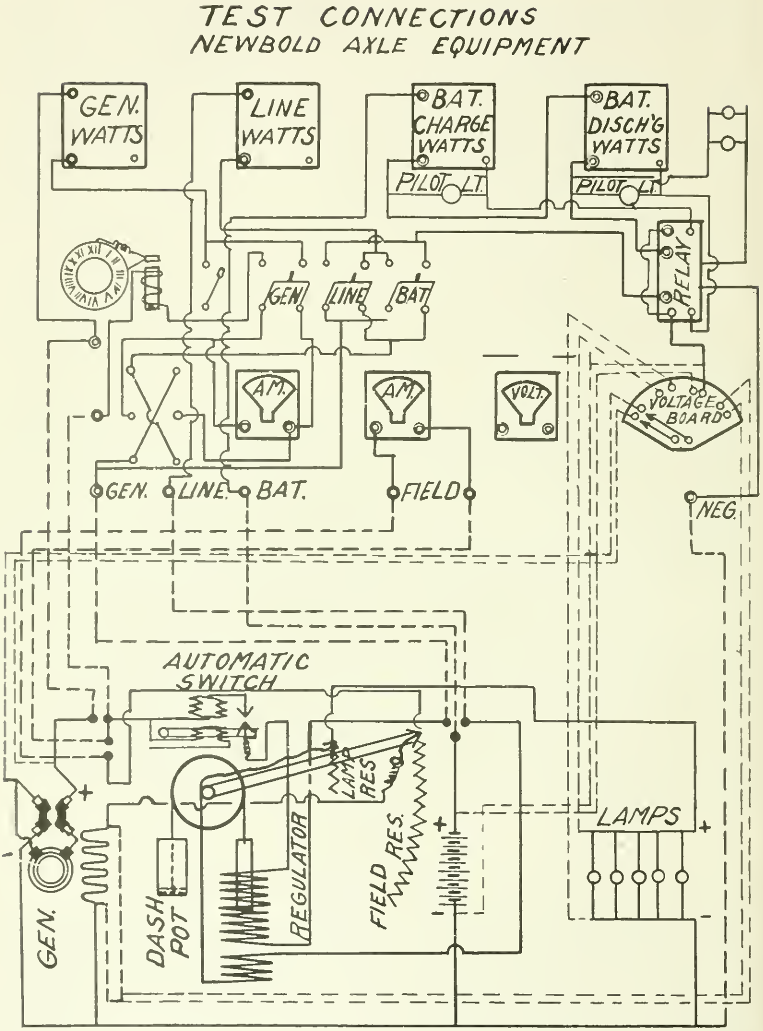

PLATE XXX.—TEST CONNECTIONS, NEWBOLD AXLE EQUIPMENT.

RESULTS OF TEST

St. Paul to Portland. March 21 to 28, 1906.

Duration of test	74	Hrs.
Generator Operating	53	Hrs.
Generator not operating	21	Hrs.
Lamps Lighted	35	Hrs.
Battery Charge	39	Hrs.
Total Generator Output	105	K. W. Hr.
Total Lamp Consumption	54.3	K. W. Hr.
Total Battery Charge	56	K. W. Hr.
Total Battery Discharge	9.7	K. W. Hr.
Average Generator Efficiency	80%	

Power absorbed from axle at 60 mi. per hr. = 3.4 H. P.

Total efficiency of run =

$$\frac{\text{Lamp Cons. x Gen. Eff. x Belt Eff.}}{\text{Gen. Output}} = \frac{54.3 \text{ x } 80\,\% \text{ x } 97\,\%}{105}$$

= 40% total efficiency of run.

Belt loss is assumed as 3%.

Portland to St. Paul.

Duration of test	66	Hrs.
Generator Operating	51	Hrs.
Generator not operating	15	Hrs.
All Lamps Lighted	34	Hrs.
Battery Charging	32	Hrs
Total Generator Output	95.5	K. W. Hr.
Total Lamp Consumption	55.7	K. W. Hr.
Total Battery Charge	42.5	K. W. Hr.
Total Battery Discharge	10.7	K. W. Hr.
Average Generator Efficiency	80%	

Power absorbed from axle at 60 mi. per hr. = 3.4 H. P.

Total efficiency of run =

$$\frac{\text{Lamp Cons. x Gen. Eff. x Belt Eff.}}{\text{Gen. Output}} = \frac{55.7 \text{ x } 80\,\% \text{ x } 97\,\%}{95.5}$$

= 45.3% total efficiency of run.

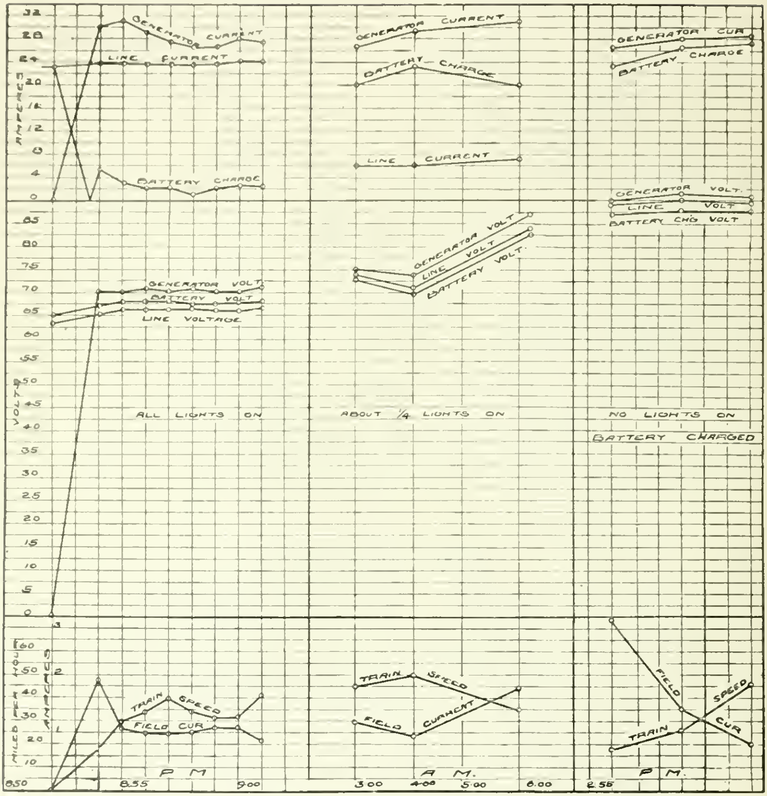

Plate XXXI.—Showing Detail Operation of Newbold Axle Equipment on Coach No. 962, Nor. Pac. Ry.

The regulator might safely be adjusted to bring the generator current to 20 amperes instead of 28 amperes, with resulting saving of battery depreciation and economy in power.

DISCUSSION OF TEST

The most striking result of the test and one of critical importance to the life of the equipment is the fact that the batteries are destructively overcharged as shown by a comparison of the wattmeter readings of battery charge, 56 K. W. Hr., page 85, and battery discharge, 9.7 K. W. Hr., also by a comparison of total generator output 105 K. W. Hr. and total lamp consumption 54.3 K. W. Hr. This is due to the fact that the regulator is set so undesirably high.

Another point of special note is that the lamp voltage follows directly the rise in battery voltage as shown by a comparison of the voltage curves in the three columns; that in the first column representing normal operation at night with all the lamps lighted; that in the second column representing the rise in battery voltage from normal to the nearly charged condition of the battery at 5:45 A. M.; while that in the third column represents an overcharging condition. It is to be observed that any lights in use during the time represented by the conditions indicated by the second column receive this enormous rise in voltage and are accordingly rapidly destroyed. It should also be noted that, had all the lights been left lighted all night, this great rise in voltage would not occur, but the operation would have continued practically constant following the conditions represented by column 1.

Incidentally it may be observed that the field current of the generator varies inversely with the train speed.

Referring to curves on Plate XXXII, the curve of battery voltage indicates the condition of battery charge, and shows that by noon the batteries had become fully charged and that all the rest of the day they were destructively overcharged. This again substantiates the point indicated earlier, that the regulator was not adjusted for the most economical conditions of use. An overcharge of a half hour occasionally is a good thing to keep the

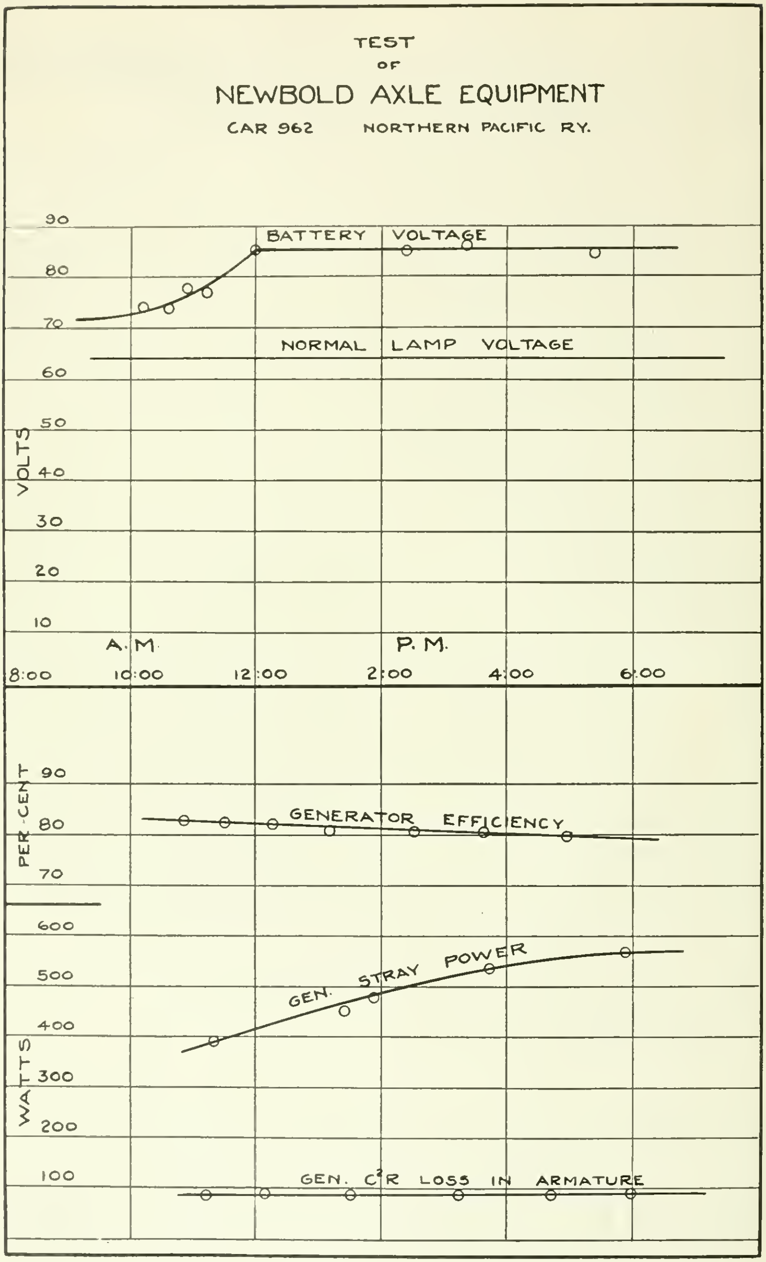

Plate XXXII.—Test of Newbold Axle Equipment, Nor. Pac. Ry.

battery from becoming sulphated, but an overcharge of six hours every day at the normal rate is sure to cause complete and rapid destruction of the battery besides a large waste of power.[8]

TEST OF NEWBOLD AXLE EQUIPMENT

ON DINING CAR "HANNIBAL,"

C. B. & Q. RY.

The equipment in this test is on exactly the same principles of operation and design as the Newbold equipment tested on the Northern Pacific Railway and described on page 77, except for the fact that this equipment operates at 30 volts instead of 60 as was the case on the other equipment.

This equipment is of special interest in that it operates under exceedingly heavy duty, the normal lamp current being 75 amperes, and moreover it is operated on a short run where it must maintain itself under markedly different conditions at the different seasons of the year: that is, in the winter months it must maintain the lights lighted not only on the run but must furnish light for about two hours while standing in the yards at Chicago, and on the return trip must maintain lights while on the run and also for an hour while standing in the yards. On the other hand, in the summer months the lights are turned on for only about an hour and a half altogether.

The car was put into service in March, only about two months before the test was made, so that it had not experienced any winter service at that time.

It operates on a short run of about 100 miles from Chicago to Mendota, Ill., leaving Chicago at 6:10 P. M. and arriving at Mendota at 8:05 P. M., where it remains till 5:56 A. M. the next morning, when it returns to Chicago, arriving there at 8:00 A. M.

METHOD OF TEST

The same methods were employed in this test as were used in all the other tests of axle equipment, and they are discussed on

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[8] For the complete data of this test refer to the graduating thesis of O. B. Cade and A. J. Walsh, University of Wisconsin, 1906.

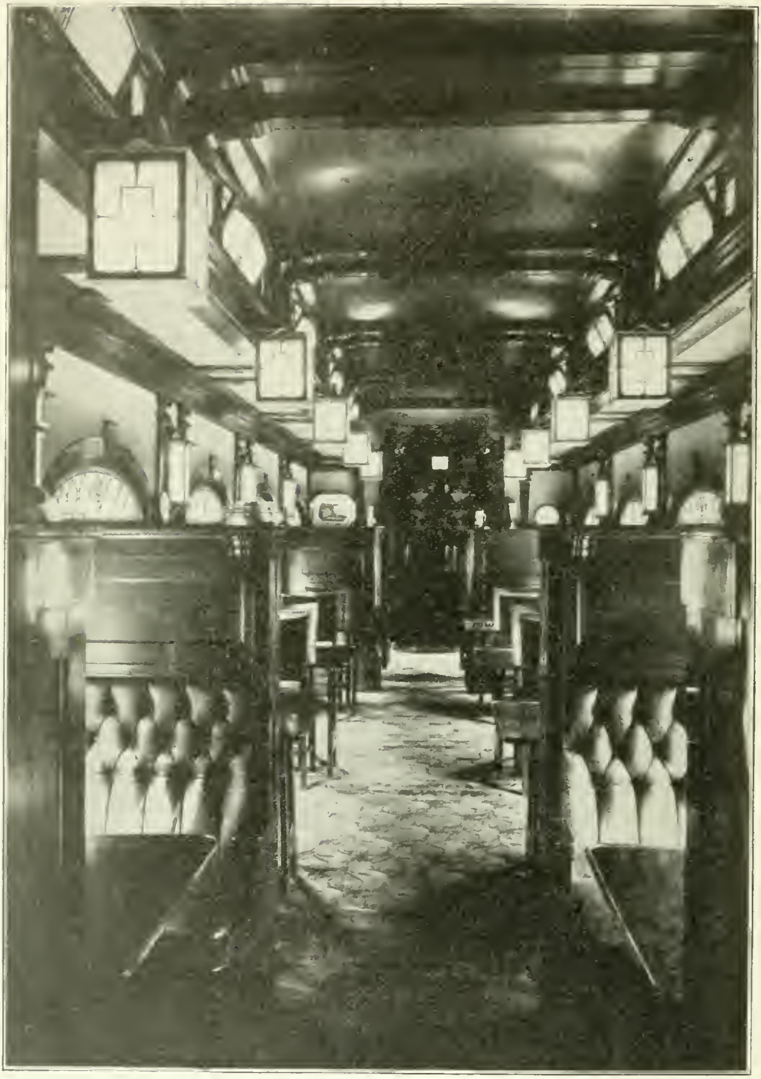

PLATE XXXIII.—INTERIOR OF DINING CAR "HANNIBAL."

page 60 so will not be repeated here, except to indicate the location of the instruments. There was of course no available room within the car (which is a dining car) for the location of a test board, except a very small space in the regulator locker. Accordingly, the switches, voltmeters, and ammeters were placed in this locker, while the larger instruments, such as the wattmeters, relay and clock, were placed in the vestibule, and all wiring connections were made to them as shown in Plate XXX. The lower half of the plate indicates the wiring connections of the axle equipment while the upper half shows the test instruments, the dotted lines indicating the connections between the instruments and the axle equipment. The heavy lines indicate No. 4 wires while the finer lines indicate voltage leads. It should be noted that special voltage leads were run from the generator, line, battery and field winding.

In testing this equipment, three round trips were made, two under normal operating conditions of that date, May 15, which is by the way near the summer solstice, and one trip under such conditions artificially produced as would be probably experienced in the winter months, that of receiving a discharge at half load for two hours in the yards before leaving in the evening and for one hour on returning in the morning.

RESULTS OF TEST

Trip 1.

Duration of test (round trip)	3 hr. 59 min.
Generator operating	3 hr. 22 min.
Total generator output	9.64 K. W. Hr.
Total lamp consumption	5.24 K. W. Hr.
Total battery charge	3.82 K. W. Hr.
Total battery discharge	1.2 K. W. Hr.

Trip 2.

Duration of test	3 hr. 59 min.
General operating	3 hr. 15 min.
Total generator output	9.36 K. W. Hr.
Total lamp consumption	6.26 K. W. Hr.
Total battery charge	3.86 K. W. Hr.
Total battery discharge	1.6 K. W. Hr.

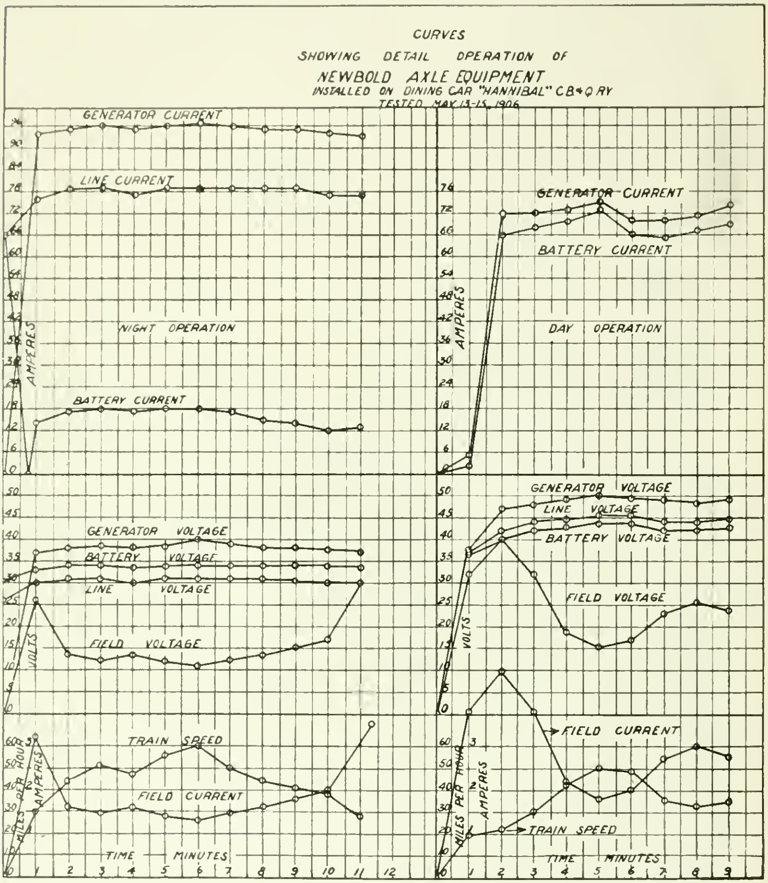

Plate XXXIV.—Curves Showing Detail Operation of Newbold Axle Equipment, C. B. & Q. Ry.

Trip 3.—Winter Conditions.

Duration of test	5 hr. 35 min.
Generator operating	3 hr. 10 min.
Total generator output	9.62 K. W. Hr.
Total lamp consumption	12.42 K. W. Hr.
Total battery charge	1.04 K. W. Hr.
Total battery discharge	4.66 K. W. Hr.

General.

Generator efficiency—Night operation = 70%
Day operation = 74%

$$\text{Total efficiency, trip 1} = \frac{5.24 \times 72\% \times 97\%}{8.64} = 42.5\%.$$

DISCUSSION OF RESULTS

The results of this test as shown by tables above, and by Plates XXXIV and XXXV, show many interesting features.

In the first place the tables of trips 1 and 2 indicate a pretty fair relation between battery charge and discharge, possibly slightly too great an overcharge but not so destructive as was found in some other tests.

Trip 3 shows an entirely different relation, however, in that the batteries will not receive the proper charge during the winter, unless the regulator is readjusted. To correct for this during the winter months, so that the auxiliary gas light will not have to be used, the regulator setting should be advanced to a value of 160 amperes instead of 95 amperes at which the generator now operates. This would be far beyond the limits of capacity of the equipment as installed on this car, so that the auxiliary gas light would very likely have to be used for part of the time at least.

In the wattmeter readings, correction has been carefully made to eliminate losses due to test connections, which were accurately measured by the voltage drop method with a 0–5 scale voltmeter.

In regard to the curves on Plate XXXIV, attention should be called to the fact that the generator current is practically constant at 95 amperes for night operation but for day operation it drops to about 72 amperes.

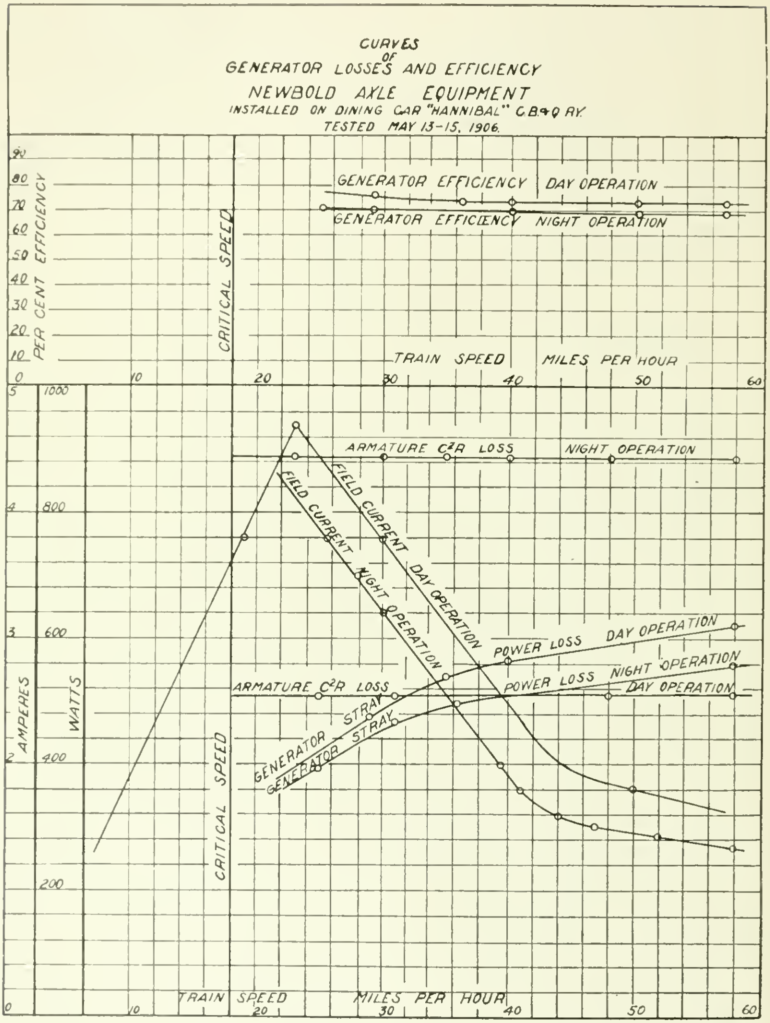

PLATE XXXV.—CURVES SHOWING THE RELATION OF THE VARIOUS LOSSES IN GENERATOR OPERATION.

This illustrates the function of the differential winding on the controlling solenoid of the regulator, which permits the generator current for night operation to be set high enough so that it will charge the batteries somewhat as well as supply the lamps, without causing excessive charging in the day time when the lamps are turned off and all the generator current is absorbed in the battery.

This is the only real value of the differential winding, but it may be said that this is sufficient to warrant its use.

The lamp voltage varied from 25 volts with the generator out of action to 32 volts with the generator in action. It should be noted that in the second column of curves the battery voltage has risen to about 43 volts, which is about 2.7 volts per cell, indicating not only a charged condition of the battery but that of overcharge at a high rate of current flow. In this connection, also, attention must be called to the fact that the battery is not of sufficient capacity for the heavy duty to which it is put.

To illustrate this point: the battery is composed of 16 "National" cells each of 336 ampere hours capacity, supposed to operate at a normal rate of 42 amperes, but it is used on a 75 ampere lamp circuit and is charged at a 72 ampere rate. While this rate would not be considered excessive for short periods of time, it cannot be considered good practice in this instance, as such a high rate causes abnormally high depreciation of the cells.

Test of Bliss Axle Equipment on the Northern Pacific Railway

The equipment manufactured by the Bliss Company is on radically different principles of control from any of the other axle devices and a consideration of the equipment is intensely interesting and instructive.

It consists essentially of a generator located on the truck and driven from a car axle, a storage battery auxiliary such as is common in the other equipments, an automatic switch to close the generator circuit when the critical speed is attained, a regulator to compensate for variable train speeds, and the lighting circuits and fixtures within the car. Within the last year or two the Bliss Company have adopted the belt drive for their generator but the equipment tested was arranged with a gear drive, accordingly the equipment as tested will be first described.

The generator is of the four pole, iron clad type, suspended inside the truck and geared to the axle by means of a driving gear mounted on one end of a split sleeve or quill surrounding the axle as illustrated in Plate XXXVII. This split sleeve is driven from the axle by means of four driving springs connected to a two armed dog, as illustrated in Plate XXXVI.

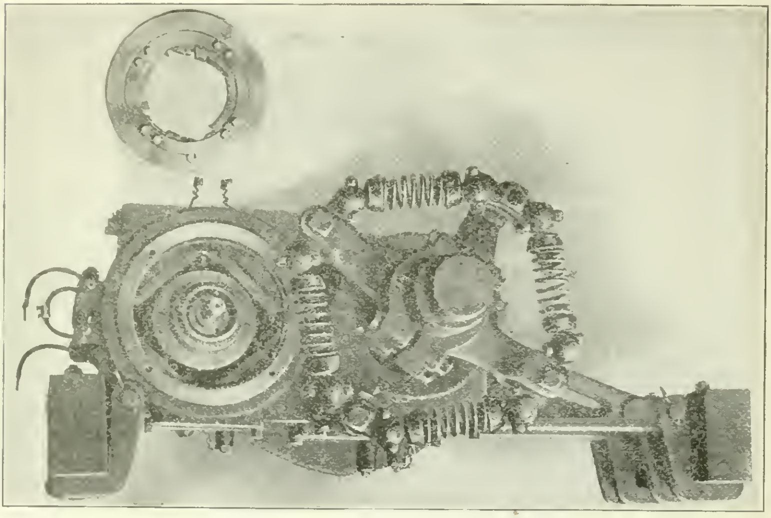

PLATE XXXVI.—SHOWING DRIVING SPRING AND GENERATOR SUSPENSION OF BLISS EQUIPMENT.

The details of the split sleeve are best seen in Plate XXXVII. It runs in and is supported by two sets of roller bearings which are in turn supported by the generator frame so that none of the weight comes upon the car axle, but is all supported by the truck frame. A large clearance is provided between this sleeve and the car axle to allow the axle to take various positions, which it does at high speed, without affecting the generator motion. Since the only connection between the generator and axle is by means of the driving springs, the generator is relieved of all the jarring and blows it would otherwise receive.

It is obvious that with so flexible a connection no careful alignment of the generator and axle is necessary. All the trueing up and lining up are done in the manufacture of the equipment, and its installation is a simple matter.

The generator and driving mechanism are encased in dust-proof cases and are supplied with self-oiling bearings.

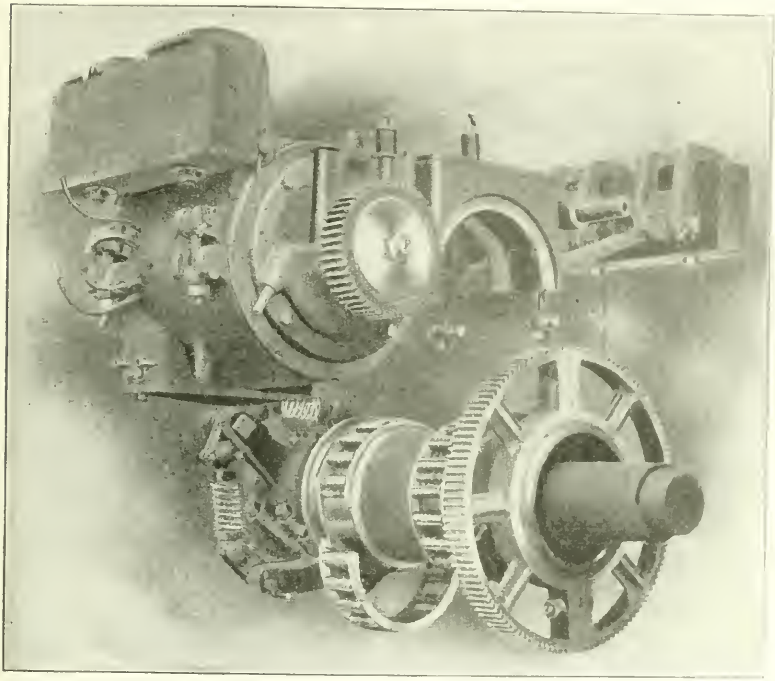

Plate XXXVII.—Showing Split Sleeve and Driving Gear of Bliss Axle Equipment.

The *regulator* is the characteristic part of this equipment. Instead of regulating the generator voltage by means of a variable field rheostat, as is done in nearly every other type, a variable electro-motive force is inserted in the generator field circuit in opposition to that impressed by the generator.

This is accomplished by means of a small auxiliary "bucker" armature driven at practically constant speed by a small shunt motor. The excitation for this auxiliary armature is furnished by the battery charging current, so that the electro-motive force developed in the auxiliary armature is proportional to the battery charging current flowing.

The principle underlying the operation of this regulation is that the charging current flowing into a battery is directly proportional to the rise in impressed voltage above the normal battery voltage; that is, assuming a normal voltage of 64 volts, there will be twice the charging current flowing if 68 volts be impressed than if 66 volts only were impressed, and further there will be three times the current flowing if 70 volts be impressed, etc.

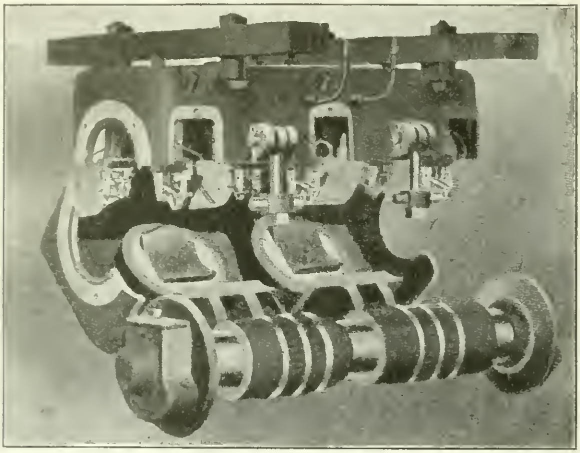

PLATE XXXVIII.—SHOWING "BUCKER" WITH ARMATURE REMOVED.

The application of this principle to regulation of generator voltage in this equipment is that a rise in train speed causes a proportionate rise in generator voltage, this in turn causing a proportionate rise in charging current, and this as above mentioned, causes an increase in the bucking electro-motive force in the generator field circuit, resulting in a decrease in field voltage and consequent decrease in field current, and this finally compensates for the rise in train speed. The regulator which effects this generator control is called the field bucker as it operates in the field circuit of the generator.

The lamp bucker is an additional bucker armature which is very similar in operation to the field bucker, but is used for the purpose of maintaining practically constant voltage on the lamps. It is wound on the same armature as the field bucker and so receives the same excitation, as described above, and generates a counter E. M. F. in the lamp circuit which is at all times proportional to that excitation. This counter E. M. F. compensates for the slight variation in generator voltage caused by varying train speeds, for obviously, as the train speed rises, the generator voltage and battery charging current will rise proportionately, this being necessary to produce regulation. The counter E. M. F. developed in the lamp bucker armature, however, is at all times proportional to the rise in generator voltage above normal battery voltage, and in proper design is made equal to it, so that this lamp bucker voltage at all times compensates for the variation in generator voltage which is inherent in the operation of this equipment. The lamp voltage is thus entirely independent of the speed of the train.

This lamp bucker armature is automatically short-circuited when the lights are being supplied with current from the battery and no regulation is necessary; this is accomplished by the triple contact shown in Plate XXXIX directly over the automatic switch. There are two triple contacts shown in the plate but they represent the same thing, being shown in duplicate only to avoid confusion of lines.

The *automatic switch* is that part of the equipment which causes the generator to be cut into the circuit at the proper speed. Its construction is plainly shown by the wiring diagram in Plate XXXIX and consists essentially of a large coil of fine wire placed across the terminals of the generator, so that when the generator voltage rises to a value equal to that of the battery, the magnetism developed in this coil will be sufficient to draw up the plunger and close the generator switch. There is an additional winding of coarse wire through which all the generator current passes, which intensifies the magnetic pull on the plunger and insures good contact at the switch. This has also

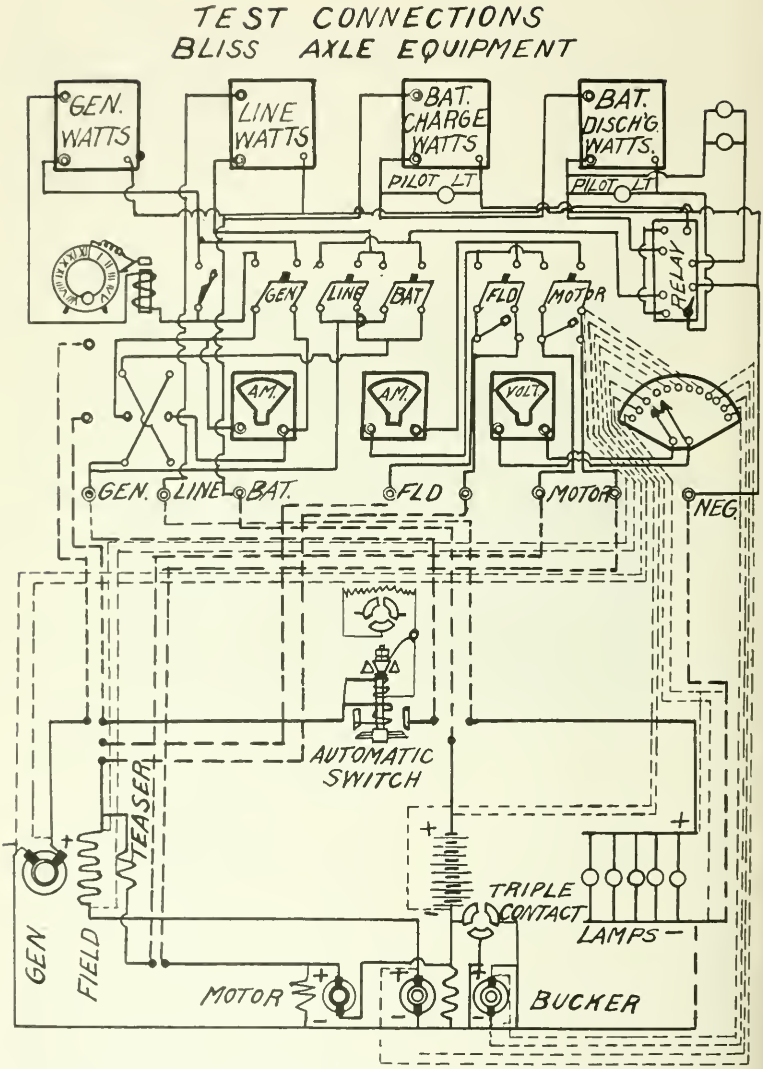

Plate XXXIX.—Test Connections, Bliss Axle Equipment.

an important function in opening the switch on decreased speed, in that the reverse current from the battery will partially neutralize the shunt coil magnetism and cause the switch to open readily at the proper time.

The *battery* is a set of 32 cells of the National type and is of 180 ampere hour capacity. The plates are set in hard rubber jars which are placed in wooden trays in pairs and the whole battery located in two boxes beneath the car as illustrated in Plate XXV on page 70.

POLE CHANGING DEVICE

In this equipment a novel device is employed in obtaining proper polarity in the generator circuit independent of the direction of motion of the car. In that the generator is a four pole one, four brushes are employed. being set 90 degrees apart. These are placed on a movable brush holder which is mounted on a support which permits the holder to rotate 90 degrees, but this support is attached to the frame of the machine.

This angular displacement is limited by a stop. When the direction of motion of the car is reversed it is obvious that the generator will develop reverse polarity. but due to this friction displacement of the commutator brushes the polarity of the circuit would also tend to be reversed. so by this double reversal, constant polarity in the external circuit is obtained.

METHOD OF TEST

In making the test of this equipment it was decided to take the data, as was done in the other tests of axle equipment. in two sets; one set covering the whole performance of the equipment and consisting of wattmeter readings of total watts generated, total line consumption, total battery charge and total battery discharge over the entire trip; the other set being concerned only with the details of operation of the equipment, consisting in taking simultaneous readings of all the various currents and pressures throughout the system as they vary with train speed.

Accordingly a test board was constructed as is shown by the upper half of Plate XXXIX, the lower half of the plate being a diagram of connections of the equipment as in normal operation, the dotted lines showing the temporary wiring to the test board.

Four wattmeters of the ordinary recording type were employed, two Thomson meters and two Duncan meters. The two Thomson instruments were placed in the generator and line circuits, while the two Duncan meters were both placed in the battery circuit, one for battery charge and the other for battery discharge.

Plate XL.—Test Board as Installed in Coach 963, Nor. Pac. Ry.

The separation of battery charge and discharge by means of a polarized relay has been explained on page 62 so will not be considered here further.

A recording clock magnetically controlled was constructed to indicate the total time of generator operation, or more correctly, the total time the generator was not operating, from which the former could easily be deducted. The solenoid of this clock was placed in the generator circuit so that with normal generator current flowing the solenoid would be sufficiently magnetized to draw down the keeper which was in connection with the balance wheel of the clock, similar to an ordinary stop watch. The adjustment was such that when the keeper was drawn down it would stop the clock, and when the generator current became sufficiently weak the keeper would be drawn up by a spring and the clock would start running, thus recording the time that the generator was inoperative.

A voltage board was constructed as illustrated in Plate XXXIX in order to make all the various voltages readily accessible for reading on one voltmeter.

The method of connection between the test board and equipment is self-evident from Plate XXXIX. The heavy dotted lines indicate where No. 3 wire was used and the fine dotted lines indicate voltage leads. No. 3 wire was used for all main circuit connections so that the error due to test connections might be negligible. Where a circuit was broken in order to insert test instruments into the circuits of the equipment it is indicated by two, and in one case three, solid black dots, which it must be understood, are connected together in normal operation of the equipment.

DATA

Wattmeter and clock readings were taken each morning when the lights were turned off and each night when they were turned on again.

The *detail data* were obtained by taking simultaneous readings of train speed, generator current, line current, battery current, field current, motor current, and generator voltage, line voltage, battery voltage, field voltage, lamp bucker voltage, and field bucker voltage. While it was impossible to make these readings exactly simultaneously they were very nearly so, in that all the readings of each set were taken within a period of ten seconds.

Train speed was determined by counting the rail clicks. In case of a 30 foot rail the number of clicks in approximately 20½ seconds is directly the speed in miles per hour. This was a very convenient and sufficiently accurate method. In taking the speed readings during test, rails were counted for 10.2 seconds only in order to facilitate the taking of these data.

RESULT OF TEST

(See also Plates XLI and XLII.)

Total time of test	74 Hrs.
Generator Operating	49½ Hrs.
Generator Not Operating	24½ Hrs.
Total Generator Output	57.9 K. W. Hrs.
Total Lamp Consumption	28.4 K. W. Hrs.
Battery Charge	8.5 K. W. Hrs.
Battery Discharge	7.3 K. W. Hrs.
Generator and drive efficiency, night operation, computed on basis of belt drive with 97% efficiency	68%
Generator efficiency, day operation, computed on basis of belt drive with 97% efficiency	50%

Average losses of gear drive = 900 watts — 1.2 H. P.

Shortly after starting upon the return trip one of the main driving springs broke and in flying around tore loose one of the generator terminals, and the test was therefore discontinued before the end of the complete round trip.

DISCUSSION OF RESULTS

Referring to Plate XLI which is merely a graphical representation of two different sets of data as taken on the road test, the set in the first column being taken in the evening shortly after the lights were turned on, and the set in the second column being taken in the middle of the afternoon while the lights were out.

One of the most important things to be noted in the first column is the curve of lamp voltage regulation, which is seen to vary from 56 to 58.5 volts in going from a stop to a speed of 50 miles an hour. This compares very advantageously with similar curves of tests of other equipments.

It should be noted also, that the battery charging current is entirely independent of the number of lamps burning, and accordingly continues throughout both day and night. This

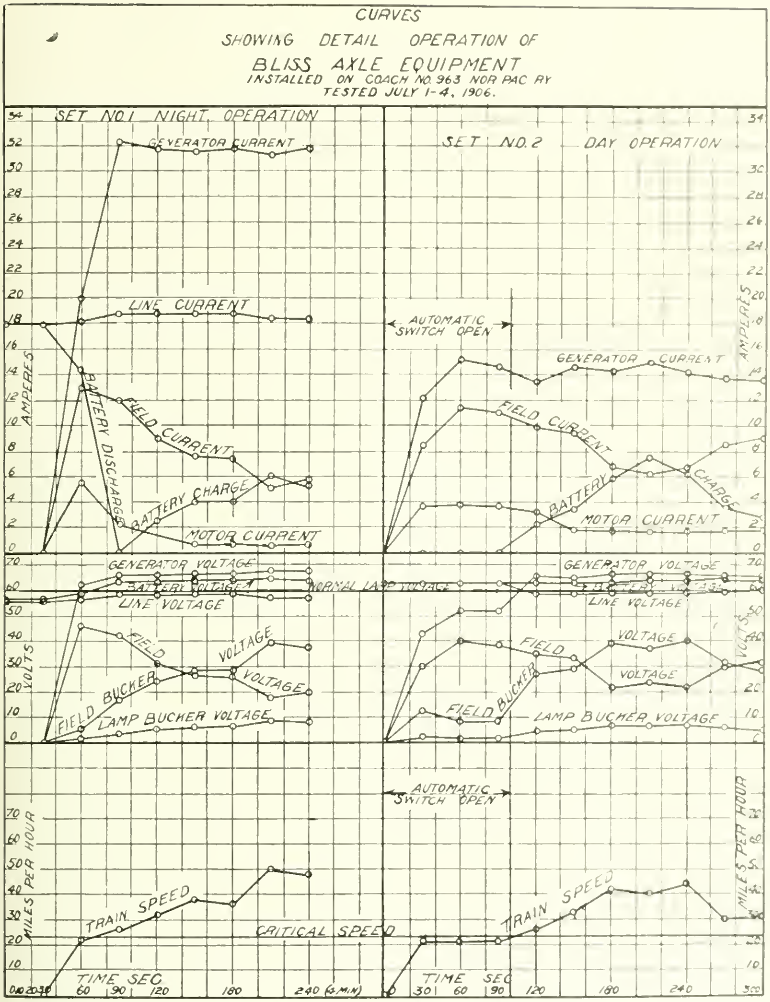

Plate XLI.—Curves Showing Detail Operation of Bliss Axle Equipment, Nor. Pac. Ry.

charge is, however, dependent upon the train speed, being zero at 25 miles per hour, and gradually rising with the train speed to a value of 8 amperes at 50 miles per hour. This point is more clearly shown in the corresponding curve on Plate XLII in which train speed is plotted horizontally and charging watts plotted vertically. This shows the absolute relation between train speed and battery charge. Here it is plotted as battery watts simply for convenience in comparison, but the approximate charging current is easily obtained by dividing by the normal battery voltage of 60.

This curve is the key to the regulation of the equipment, in that the equipment is operated on principles of battery current regulation, and accordingly the greater the speed the greater the battery current necessary to compensate for that rise in speed. Referring again to Plate XLI it should be noted that the battery charge, field bucker voltage and lamp bucker voltage, increase directly with the train speed, while the field current and field voltage, and motor current vary inversely with the speed. All these relations are shown more plainly by curves on Plate XLII and will be reverted to later.

Comparing the two columns on Plate XLI it may be seen that the operation in the two conditions illustrated is essentially the same except for the change in lamp current, this causing merely a corresponding decrease in the generator current. It should also be noted, before leaving this plate, that the generator current is practically constant at all speeds when the number of lights remains constant. This is due to the fact that for rise in speed the battery current increases while the field current decreases by an approximately equal amount, so that they compensate for each other.

The character of the operation of the equipment may be summarized as follows:

1. The equipment regulates lamp voltage admirably, irrespective of train speed or number of lamps in use, but does not fully regulate in respect to variation in the condition of the battery.

2. The batteries are charged both day and night entirely independently of the lamps in use. This is a point of advantage in

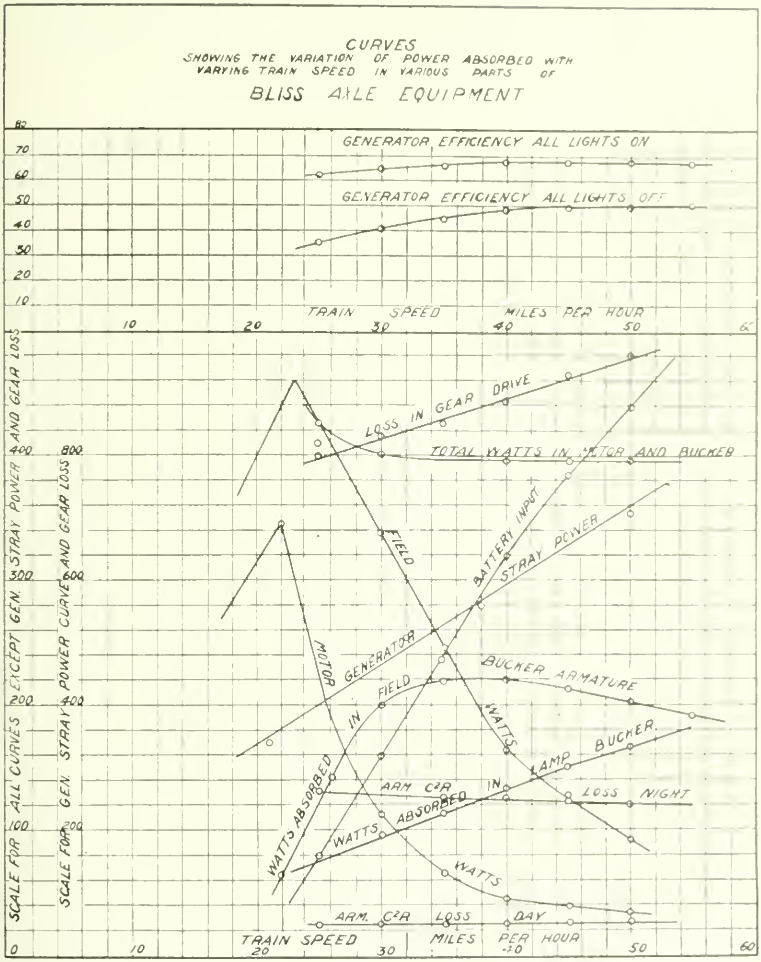

PLATE XLII.—CURVES SHOWING THE VARIATION OF POWER ABSORBED WITH VARYING TRAIN SPEED IN VARIOUS PARTS OF BLISS AXLE EQUIPMENT.

that it allows the equipment to recover at night from a severe discharge. This is not generally the case with the constant current regulation of most other equipments. It also provides that the battery be charged at a low rate over long periods, which is a desirable feature.

3. Battery charging current maintains a fixed relation to train speed independent of the condition of the battery. This has certain advantages and other disadvantages.

Test of Straight Storage Equipment

C. B. & Q. Railway

The test of this equipment was made on a train running between Chicago and Minneapolis, Minn., on the Chicago, Burlington & Quincy Railway. Each car of the train was equipped with a battery of 48 cells of 160 ampere hour capacity made by the American Battery Company. These batteries are all charged and discharged together, as train line connections are made between cars. Suitable switches are supplied in a locker in each car for operating the lamp circuits. The equipment is extremely simple, as no regulating device or complicated mechanism is in the circuit.

The operation of the batteries is as follows:

A charge is given the batteries during the day at Minneapolis, which is followed by the discharge during that night on the run to Chicago. At Chicago the batteries are again charged all day and the night following are discharged in lighting the train on its return to Minneapolis. The charging at Minneapolis is accomplished by means of a Westinghouse gasoline engine-generator set. As soon as the train is backed into the yards, the connections are made to the train line and the charging begins without removing the batteries. Except for a shutdown from 12 to 1 at noon, the batteries are charged continnously from 8:30 A. M. to 5:30 P. M., using a current of about 40 amperes to the train of four cars.

At Chicago the batteries are again charged for about the same period from a charging station at the 12th Street Round House, which is provided with a 90 Horse-power Westinghouse Engine belted to two dynamos, one of 15 K. W. capacity and the other of 25 K. W. capacity.

METHOD OF TEST

In making the test of this equipment, switches were placed in the battery circuits of each car by means of which an ammeter could be inserted to measure the current flowing. Readings of current and voltage were taken from each car at fifteen minute intervals. The results given in the following table are the averages of three separate charges and three separate discharges which were made in the test.

RESULT OF TEST

Chair Car No. 501.

total lamp consumption (3 trips)	17.94 K. W. Hr.
Total battery charge (3 days)	38.6 K. W. Hr.
Watt efficiency	46.5%
Total lamp consumption (3 trips)	20.9 K. W. Hr.
Total battery charge (3 days)	45.7 K. W. Hr.
Watt efficiency	45.7%

Pullman Sleeper "Apollo".

Total lamp consumption (3 trips)	26.1 K. W. Hr.
Total battery charge (3 days)	51.9 K. W. Hr.
Watt efficiency	50.3%

Chair Car No. 4151.

Total lamp consumption (3 trips)	17.4 K. W. Hr.
Total battery charge (3 days)	31.5 K. W. Hr.
Watt efficiency	55.2%

DISCUSSION OF RESULTS

In discussion of the results of this test, attention should be called to the low efficiency of the batteries as given on the preceding page. This is largely due to the fact that the batteries were old ones and had been operated in this service for several years. It is also somewhat due to the fact that the batteries were slightly overcharged each day, this, however, not being much more than should be given to keep the plates from sulphating.

In regard to the general operation of the equipment it may be said to be satisfactory. The lights at the beginning of the trip are connected to a freshly charged battery and make a very good showing in lamp brilliancy. Later in the night the voltage falls somewhat, but the lights are not needed so much at that time, so that it is not objectionable.

CHAPTER IV

THE AXLE LIGHTING PROPOSITION

In presenting this chapter it will be assumed that the reader has a practical understanding of the ordinary apparatus in connection with an axle equipment, such as the generator, battery, lamps, pole changer, automatic switch, regulator, etc., and in this chapter will be considered only the principles underlying the operation of that equipment.

The fundamental principles will be treated in the order of their importance and may be outlined as follows:

a. Generator control.
b. Lamp voltage regulation.
c. Generator drive.
d. Protection of storage battery from excessive overcharge.

(a) *Generator Control.*—There are several principles upon which such a control might operate, and there are as many such regulators in actual operation.

1. Probably the simplest one is that which depends upon the belt slipping at the high speeds so that the generator runs at a constant speed irrespective of variable train speed above a certain predetermined limit. Such an equipment is described on page 11.

2. Then another might be dependent upon armature reactions at the high speeds controlling the generator voltage. Such an equipment is described on page 16.

3. Regulation could also be effected by means of a differential winding on the generator fields to decrease the excitation as the generator voltage, and hence battery current, increased. Such an arrangement is sometimes employed, where desirable,

as a modification of the Bliss Axle equipment, replacing the bucker scheme.

4. The last and most used in this country is that type of regulation which controls the generator current by varying the generator field current to compensate for rise in speed. Upon this last principle are based all the successful regulators in the American market today.

In the manner in which this variation in field current is obtained proportionate to rise in train speed, there is a wide diversity of methods and mechanisms. They may, however, be divided into three classes; those of Constant Current Control, Battery Current Control and Voltage Control.

Further, it is interesting to note in a comparative way the various means by which the regulation is effected.

1. In the Consolidated Axle Equipment a field rheostat is operated by means of an auxiliary motor. See page 56.

2. In the Newbold System the floating plunger of the solenoid is attached to a balanced rheostat arm. See page 77.

3. In the United States Equipment the floating plunger of the solenoid presses directly upon a pile of carbon blocks which forms a variable resistance in multiple with the generator fields. See page 21.

4. In the Deutsch System a field rheostat is operated by compressed air, the supply of which is affected by the controlling solenoid. See page 25.

5. In the Everett Regulator a variable resistance in the form of carbon contacts is inserted in multiple with a permanent field resistance, these carbon contacts being fastened directly upon the floating plunger itself. See page 24.

6. In the McElroy Axle Equipment a small auxiliary motor operates the field rheostat, the motor running only when regulation is necessary. This motor is controlled by the regulating solenoid. See page 18.

7. In the Bliss Axle Equipment a small motor drives an auxiliary armature which generates a variable counter-electromotive force in the generator field circuit. This is better known as the "bucker," and is described on page 98.

The first class of regulators, those of constant current control, comprise all those regulators which depend upon the magnetic pull of a solenoid energized by the generator current. Of the modern American equipments on the market, those having this type of regulation are:

The Consolidated Axle Equipment	p. 56.
The Newbold Axle Equipment	p. 77.
The United States Axle Equipment	p. 21.
The Deutsch Axle Equipment	p. 25.
The Everett Aegulator	p. 24.

In the second class, that of battery current regulation, there is only one equipment manufactured, the Bliss Axle Equipment, page 95.

Likewise in the third class, that of voltage control, there is only one equipment in the American market, the McElroy Axle equipment, page 18.

In a consideration of the relative merits of these three classes of regulators, it should be remembered that none of them regulates for constant generator voltage, in fact, such a regulator would be impracticable on this kind of service, inasmuch as it is necessary to raise the impressed voltage in order to charge the battery; but the writer does, in this connection, wish to emphasize the fact that the regulators for constant generator current, as well as those of battery current control, will cause the same charging current to flow whether the batteries are in an exhausted state and need the charge, or whether they are, at the time, fully charged and are being destructively overcharged; that is, the regulation is not dependent upon the voltage at which it operates. This point is easily proved, inasmuch as the regulation itself depends upon this very current flow.

This should indicate the extreme importance of proper setting of the regulator for the conditions of each particular run on which cars are engaged, in order that the time of destructive overcharge may be a minimum. On many runs, however, this is impossible due to the uncertain and unknown conditions, and in such cases in order to obtain satisfactory and economical operation a protective device to prevent excessive charging such as described on pages 126 to 132 is desirable.

The equipment in the class operative by voltage control is that described on page 18. The principle underlying the operation of this regulator is one which should, if properly carried out, largely eliminate the objection in regard to overcharge of the battery, which is often found with the other types, for in this type of regulator the charging current decreases by any predetermined ratio as the battery becomes fully charged, as explained on page 19.

It should be noted that in the constant generator current regulation, the battery charging current when the lamps are turned on is very low or nothing at all (see Plate XXXI), but that when the lights are turned off it rises to a value equal to the normal generator output, so that the charging is practically all done in the day time; while on the other hand with battery current regulation, such as the Bliss type, the battery charge is irrespective of the lamps in use, that is, the batteries are charged practically all the time the train is running. The amount of charging current flowing varies with the train speed as shown on Plate XLI in the test of that equipment, but the average value of charging current is proportional to the average train speed above the critical speed.

A differential winding is provided on many so-called constant current regulators, which causes the generator to supply a considerably larger current when all the lamps are turned on than when they are all turned off. This permits the battery to be charged considerably during night operation (see Plates XXIII and XXXIV) as is the case also with the battery current regulation of the Bliss equipment (see Plate XLI).

This may be said to be a good point in the operation of these equipments, as it provides that the battery may recover quickly from a serious discharge even while the lamps are all turned on.

In fact in this connection it is the firm belief of the writer that, where the generator is of sufficient capacity, this differential winding on the constant current regulators should be increased to such a value that it will maintain the battery charging current practically constant throughout both day and night operation. This, as mentioned above, would provide speedy recovery of the battery from any heavy discharge and would also render equipment more independent of the variation between winter and summer operation as discussed on page 117.

Calculation of Regulator Adjustment.

In regard to the calculation of the proper adjustment of the regulator, it may be said that no definite methods of procedure can be laid down, as it varies with each type of regulation and is at best only an approximation, but in general for those regulators which maintain constant generator current and have no differential winding, the regulator should be set so that the aggregate ampere hours charge of the battery during the day time should be about twice as great as the aggregate battery ampere hours discharge at the slows and stops during the night. This should be sufficient to care for low battery efficiency and for recovery from emergency discharges. Attention, however, should be called to the fact that the batteries are discharged at night not only while the train is stopped but all the time it is below the critical speed of about 20 miles per hour, and the estimation of the ampere hours discharge must be based on this time. This must be given special attention when running slow on mountain travel or running through the yards near a large city where slow speed is necessary.

In making the calculation above, it must be considered whether or not the generator current at the setting calculated is larger than the normal lamp current added to the average field current, and proper correction be made for this all-night charge or discharge as the case may be.

In making calculation of the proper setting when a differential winding is added to the regulator the problem is more complicated and liable to error, but in general the same method may be followed as is mentioned above in connection with constant generator current regulators, except that the difference between the operation when the lamps are all on and are all off must be kept in mind. In allowing for this difference in operation it must be remembered that the difference is caused by the lamp current flowing through the differential winding, so that the difference between the day operation without the lamps on and the night operation with all the lamps on is constant whatever be the regulator setting. That is, if the regulator is set at 30 amperes in day operation and 40 amperes with all lights on, and then the regulator be changed so as to deliver 35 amperes in the day operation, the night operation will be correspondingly increased to 45 amperes, etc.

When making calculations for the setting of regulators in connection with Pullman sleepers where about two-thirds of the lights are turned off as the passengers retire, the calculation is still more complex and should be checked by experience and trial on the particular runs, as the effect of the differential winding decreases as the lights are turned off so that if the regulator had operated at 35 amperes during the day and 45 amperes when all lamps were turned on it would be operating at about 38 amperes when only one-third of the lamps were lighted; that is, there is a differential effect of only one-third normal.

The calculation for the proper setting of a battery current regulator of the Bliss type is more simple and of a smaller probable error. Since the charging current is proportional to the average train speed, or more correctly is proportional to the average train speed above the critical speed, (see page 106) all that is required in setting this regulator is to know the average train speed from the time table, the total battery discharge in ampere hours while the generator is not operating, and the total time of generator operation. The regulator is then adjusted, when the average train speed is attained, to such a value that the then obtained current multiplied by the total time that the generator is operating will give an ampere hour charge equal to about twice the total ampere hour discharge. This will ordinarily be sufficient to allow for low battery efficiency and for recovery from emergency discharges. It should be noted that no consideration need be given to the number of lamps used nor the hours of lighting, this battery charge being independent of the lamps.

It is readily apparent that the calculations given above are at best merely approximations, in that they involve many assumptions which cannot be accurately determined except by special tests. It is easy to adjust an equipment so that it gives sufficient charge to the battery, for if it does not, the fact is immediately indicated by failure of the light, but on the other hand to prevent an excessive overcharge is a more difficult matter as the battery may be practically ruined before the effect will be especially noticeable unless the battery is under careful supervision at the ends of the run.

This excessive overcharge can. however, be easily detected and remedied by placing a testing wattmeter in the battery circuit for at least one round trip of the car. This will run, say forward on charge and backward on discharge, so that the difference in the reading before and after will represent the overcharge. Not exactly so, however, for it must be remembered that the meter will measure watts charge and watts discharge, and that a proper charge must be considerably in excess of the discharge, especially where both are measured in watts. Then for proper operation of the equipment this apparent overcharge, as indicated by the meter, should be about equal to the total amount discharged from the batteries in lighting the lights when the generator is not operating. This can be readily estimated from the discharge at stations. Any railway company operating axle equipments should purchase at least one recording wattmeter of a good standard make which is of sufficiently robust construction to withstand the severe service and should use it for testing in the manner just suggested. This will provide an easy and accurate method of determining the operation of an axle equipment.

In regard to the variation of the regulator adjustment throughout different times of the year, attention should be called to Plate XLIII. The cross lined portion indicates the hours in which the lamps are lighted throughout the year. It is noted that the hours of lighting are assumed as falling within one hour before sunset and one hour after sunrise, this being about the average time as found in the pursuit of these tests.

It is noted that the variation is from 10 hours in June to 17 hours in January. This represents an increase of about 70% in the total hours of lighting in January over those for June.

In regard to the resetting of the regulator to compensate for this variation, it may be said that the necessary variation in

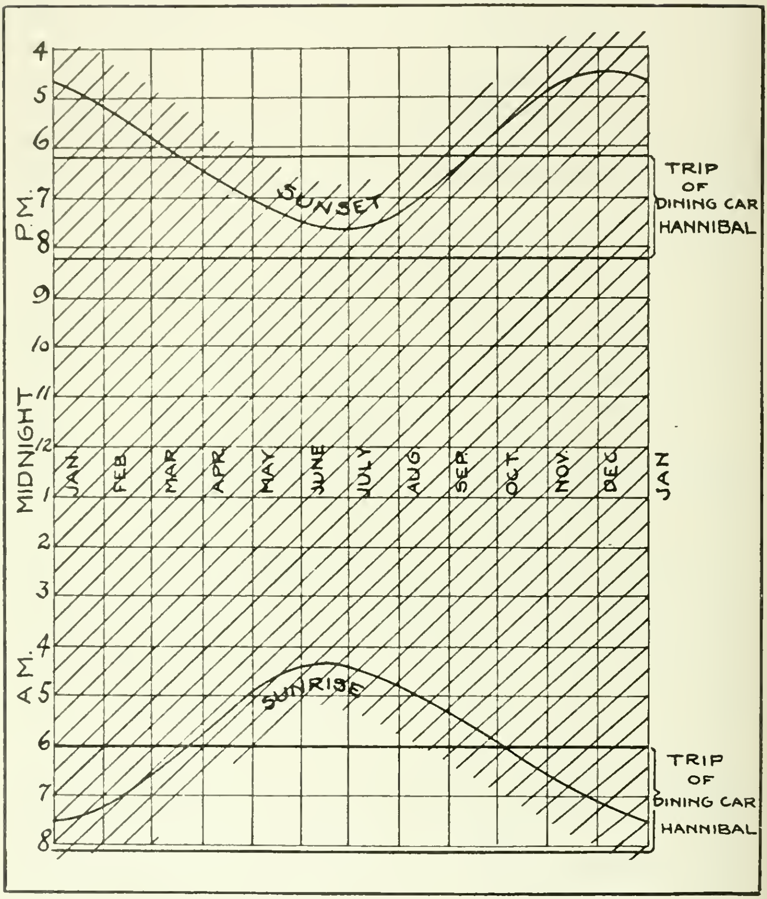

Plate XLIII.—Curves Showing Hours of Lighting.

regulator setting is of no such magnitude as 70% except in special cases, but is nevertheless of sufficient value to warrant consideration.

For constant generator current regulators which have no differential winding, it is readily seen that the increased total hours of lighting will affect the operation in two ways; it will increase the probable battery discharge at stops, and will decrease the total hours of charging the battery during the day. The former may be assumed as directly proportional to the 70% increase in hours of lighting, while the latter will be proportional to the decrease in available hours for charging the batteries which is seen to be seven hours or about 50% of the total hours available for charging outside of lighting hours during June. These combined would require an increase to 4½ times the normal rate of charge, or a 350% increase, if all the charge were to be done during the seven hours daylight run in January, but as this increase in setting will be effective throughout twenty-four hours, instead of only seven hours upon which that figure is based, the necessary increase in the average charging current will be only 100%.

It has been found in pursuit of the tests that the battery charge generally comprised about ¼ of the total output of the generator, so that reducing the calculation to a basis of generator current, it is found that: For all constant current regulators operating on trains having a 24 hour run or over, the regulator adjustment should be increased approximately 25% for operation in January over that for operation in June.

For regulators operating on principles of battery current control the situation is somewhat different. As previously indicated, the charging of the storage battery takes place all the time the train is above critical speed and is independent of the lamps. Now again, assuming the car is operated on a 24 hour run, the increase of 70% in the hours of lighting during the winter months will only affect the battery discharge and will not affect the charge, so that the readjustment of the regulator need be only such as will compensate for the increased discharge. However, inasmuch as the battery current comprises the total regulator current, this increase of 70% in the battery discharge must be compensated for by a direct increase of 70% in the regulator setting. This, however, gives a wrong impression in that apparently the necessary variation of adjustment is much greater than the 25% found in the case of the constant current regulators, but inasmuch as the regulator current comprises the whole generator current in the case of a constant current regulator, the 25% variation will represent a greater ampere variation than the 70% variation of the battery current regulator. The necessary variation in the two different systems expressed as a ratio in amperes would be approximately 9 amperes in the former and 5 in the latter.

The voltage control machine would, of course, require no readjustment other than to provide for the variation in a charging voltage due to the low temperature in the winter months.

In regard to the variation in regulator settings mentioned above, adjustment should be made perhaps four times a year, preferably March 1st, May 1st, Aug. 1st and Nov. 1st. This is allowing a probable error of 2 or 3 amperes in the adjustment, which is possibly too great for good practice, but is, however, unavoidable, due to the uncertainties of operation.

In the foregoing, consideration has been taken only of those equipments operating on a 24 hour run or over. In regard to the equipment on short runs of which the dining car "Hannibal," (page 89 and Plate XLIII) is an example, the variation is much greater and at the same time more uncertain. It has been computed on page 93 that during the summer months this regulator should be set at 86 amperes, while during the winter months this should be increased to 160 amperes, representing an increase during January of 87% over the operation during June.

This should be sufficient to emphasize the necessity of proper attention to these short run equipments. The regulator on the car in question might well be adjusted as often as once in two weeks, and even that would allow a probable error as great as 4 amperes in the adjustment at certain times.

(b) Lamp Voltage Regulation.—Before beginning the discussion of lamp voltage regulation it is important that the un-

derlying principles which make such regulation necessary be well understood.

Plate XLIV, taken from Lyndon's *Storage Battery*, represents the voltage variation of a storage battery while being charged and discharged at the normal rate. It is noted that the charging voltage is considerably in excess of the discharge voltage and that the curves are approximately parallel between (a) and (b). As the charge is continued, however, the charging voltage finally rises rather abruptly to a voltage at which it will remain so long as the act of charging is continued, this point indicating that the battery has been fully charged.

In the operation of axle equipments it may be said that the battery voltage when the lamps are turned on, oscillates back and forth between these two curves, lying on the discharge curve for a few minutes while at stations and on the charging curve while running between stations. Inasmuch as the lamps are to be operated in parallel with the battery, it is evident that the oscillation back and forth between the two curves must be compensated for if constant voltage is maintained at the lamps, so that the lamp voltage will practically follow the lower of the two curves, as is the case in most of the lamp regulators. It is noted, however, that this curve of discharge voltage which may be considered as the point of reference in most equipments, is itself not constant but varies considerably throughout the battery capacity, and it is this feature that is the neglected consideration in most lamp voltage regulators.

It must be made clear, however, that under ordinary circumstances with proper adjustment of the regulator, the battery does not become fully charged during the night, but rather operates over a range well within limits, so that the curve of reference mentioned may vary only slightly. There are, however, many cases, especially on Pullman sleepers, where the battery does become fully charged during the night, at which time the charging voltage is maintained at maximum value. At this time the "night circuit" of lamps is severely strained as indicated on Plate XXVII, page 76. This point is discussed later in the chapter in connection with the proper regulators.

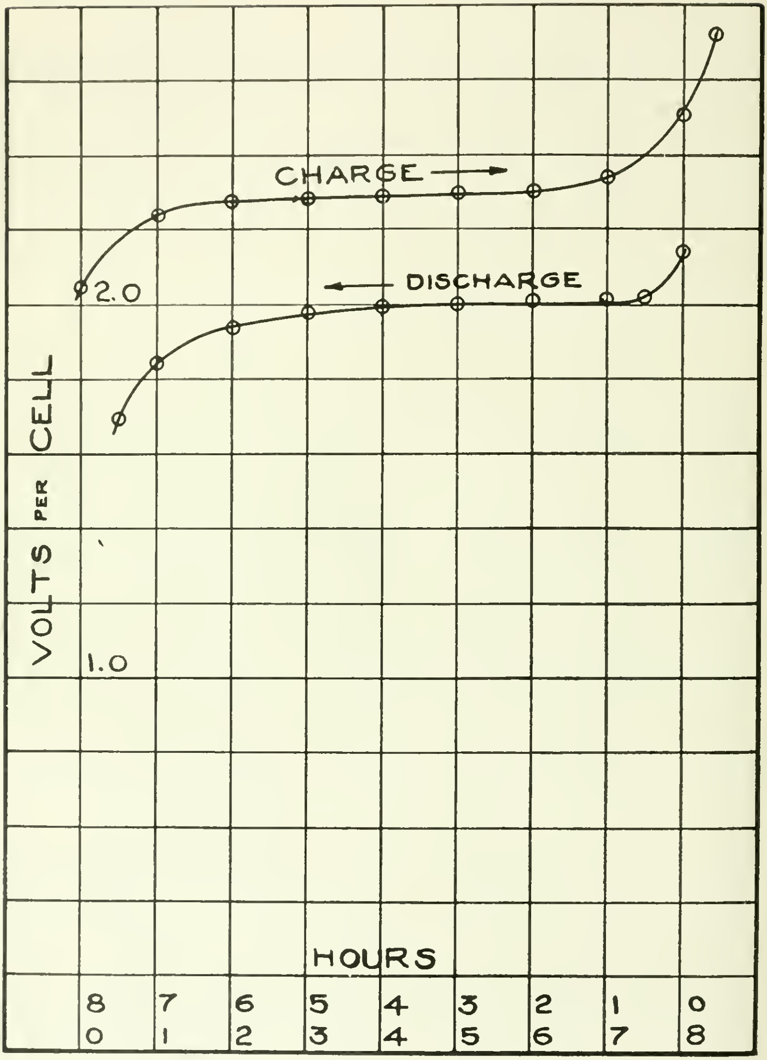

Plate XLIV.—Charge and Discharge Curves.

The oscillation of battery voltage as mentioned above makes it necessary to insert some kind of voltage drop in the lamp circuit when charging takes place, in order to compensate for this rise in voltage and to maintain constant lamp voltage. In the modern American equipment this is accomplished in four different ways:

1. By inserting a certain definite resistance in the lamp circuit when the generator first begins to operate.
2. By inserting a resistance in the lamp circuit, the value of which depends upon the number of lamps in use.
3. By automatically inserting a variable counter-electro-motive force in the lamp circuit.
4. By automatically inserting a variable resistance in the lamp circuit controlled by a special regulator.

(a) The first case of inserting a certain definite resistance into the lamp circuit is employed on numerous equipments, among which are the old type Consolidated equipments and the United States equipments. It consists in simply inserting this resistance when the generator begins to operate. This is accomplished in various ways as described in connection with those equipments and will not be considered further. In discussion of the operation of this arrangement it should be noted that this resistance is designed to compensate for the difference between the charge and discharge curves as shown on Plate XLIV, but it should be also noted that there must be normal full load lamp current flowing to produce the desired drop.

It may be said that under the conditions for which this is designed it may be made to give satisfactory regulation, but for the variable conditions as commonly met with in actual service it is not entirely satisfactory. For instance, as part of the lamps are turned off, the IR drop in the resistance will decrease proportionally, so that the lamp voltage will more nearly follow the battery voltage. At this time, with constant current regulators, the battery charging current will increase and accordingly the battery charging voltage will be increased so that the increase in lamp voltage will multiply as the lights are turned off. This type of lamp regulation will not, of course, compensate for the rise in voltage due to increased battery charge mentioned above, and the lamp voltage may be said to depend upon the number of lamps in use and the condition of battery charge.

(b) The second class, a modification of the above, is that used on the Newbold equipment and consists in connecting separate portions of the lamp circuit rheostat to the switches of the various lamp circuits, so that as each lamp circuit is turned on, a portion of the total lamp resistance will be short circuited, and, as the lamps are turned off, the total lamp resistance will be increased so that with a proper proportioning of parts the IR drop of the lamp rheostat may be said to be independent of the number of lamps in use. The Newbold regulator does not, however, compensate for the rise in battery voltage due to the battery becoming more fully charged. In fact, when part of the lamps are turned off, the battery will charge more rapidly, and though the IR drop in the lamp rheostat is independent of the number of lamps in use, the total regulation cannot be said to be independent of the number of lamps in use. In fact. this rise in battery voltage as represented by the upper part of the curves of Plate XLIV, may be such as in some cases to obliterate entirely the good offices of the variable rheostat.

This principle of making the lamp circuit rheostat vary with the lamps in use does not add any serious complication to the operation of the equipment, and the advantages gained undoubtedly warrant its use.

(c) Another type of lamp regulator is that described on page 98. as used on the Bliss equipment. It consists essentially in placing a counter-electro-motive force in the lamp circuit to compensate for the rise in battery voltage. The value of this counter-electro-motive force, as previously described in connection with the Bliss equipment, is directly proportional to the rise of battery voltage and it therefore regulates accurately in this respect.

Inasmuch as a variable counter-electro-motive force developed in a low resistance armature is employed instead of a rheostat, the lamp regulation will be independent of the number of lamps in use. The regulator does not, however, compensate for the rise in battery voltage due to a more fully charged condition of the battery, but as above mentioned, under ordinary conditions the battery is operated well within limits, so that the excess voltage of overcharge is not often attained.

The point, however, is maintained in regard to all three types of regulators thus far mentioned, that, in case *the battery does become fully charged while the lamps are burning, the lamp voltage will rise directly with the battery voltage* represented by the upper curve on Plate XLIV. This is sufficient to indicate the necessity of caution in setting the generator control so that the battery will not become fully charged at night.

(d) The last of the four types of lamp regulators mentioned above is the one manufactured by the Consolidated Axle Equipment Co., described on page 58.

It consists essentially of inserting a variable rheostat in the lamp circuit which is controlled by a special solenoid regulator and is operated by an auxiliary motor as described in the above reference. It is readily seen that, inasmuch as this regulator is controlled by an independent solenoid, it will, if properly adjusted, be entirely independent of the number of lamps in use or condition of the battery charge, and will be limited in its accuracy of regulation only by the probable error in the controlling solenoid.

(c) *Generator Drive.*—All the methods used in driving the generator from the car axle may be divided into three classes:

1. Belt Drive.
2. Gear Drive.
3. Friction Drive.

The first mentioned type, that of the *belt drive*, is the most commonly used and apparently the most successful. It has the advantage of simplicity, and is readily accessible in case of repairs. Failure of the drive due to the loss of the belt may be remedied in a few minutes. It forms a flexible connection so that the blows and shocks of the car axle are not transmitted to the generator.

The *gear drive* contains complications which render it more inaccessible and difficult to repair. Such an equipment has been described in connection with the test of the Bliss Axle Equipment, so the details of construction will not be repeated.

It may be said, however, that this kind of a drive has an advantage over belt drives under certain extreme conditions where the under rigging becomes covered with ice, but as this condition is seldom met with on most railways it may be disregarded in most cases, and the mechanical disadvantages seem to outweigh any advantages.

In regard to the power absorbed by the gear drive tested, it was found to be about 25% of the total generator output when all the lamps were turned on. This is considerably higher than that generally experienced under similar conditions of load with a belt drive which has in these tests been assumed as 3%. This assumed belt loss may be somewhat low but was considered as a fair approximation of the real conditions.

The *friction drive* is the least used of any of the drives. At an early date in his development work, Mr. W. L. Bliss devised and patented such system for use in connection with single lighting equipment and the same system with modifications is now under consideration by the Bliss Co.

(d) Protection of the Storage Battery from Excessive Overcharge.—As pointed out in this discussion, it is inherent in the operation of all current regulators to overcharge the battery to a greater or less degree, depending upon the error in setting the regulator, and as the resultant high battery depreciation is a prominent factor in the cost of "axle lighting," a consideration of methods of reducing this depreciation is at once interesting and instructive.

Prevention of this overcharge of the battery can best be effected by rendering the generator inoperative after the battery has become fully charged and maintained so whether at high or low speeds until the battery requires replenishing. Obviously this point at which the battery does become fully charged is of vital importance in this consideration and because of the peculiarly variable nature of a storage cell, the accurate determination of this point by automatic apparatus presents a problem of considerable difficulty.

Mr. W. L. Bliss has designed such an apparatus which depends for its operation upon the rise in voltage of a battery as it becomes charged. A solenoid of fine wire is placed across the terminals of the generator and when the automatic switch is closed the solenoid is also across the battery terminals. As the battery becomes fully charged its voltage will rise to such a value as will trip the solenoid plunger which opens the field circuit of the generator. This would of course reduce the generator voltage to zero and open the automatic switch, but such result would release the solenoid plunger which would fall and again re-establish the generator field and repeat the cycle of operations. What is wanted is to kill the generator to a point so low that the automatic switch will open and remain open, but it is not desired to kill the generator completely as some voltage is required to maintain the solenoid plunger in its drawn position. Accordingly, as soon as the shunt field circuit is opened, a stable, though weak field is reestablished from the battery and so a low generator voltage is maintained. This, however, even at the high speeds, is not of a value sufficient to close the automatic switch. When the train stops, the solenoid will be no longer energized and so will allow the plunger to fall, reestablishing the generator shunt field circuit. If no current has been taken from the battery since the time the cut-off operated, the cut-off will operate again very shortly after the generator becomes operative. If, however, current has been taken from the battery in the meantime, the generator will continue to operate until it has replaced this and until the battery again becomes fully charged, when the cut-off will again operate.

One car on the Pennsylvania railroad has been equipped with this controlling device, but as yet no definite information can be obtained in regard to its operation.

A controller, differing radically from that above, has recently been developed by the writer. It consists essentially of a controlling wattmeter which registers charge and discharge of the battery, rotating in one direction on charge and in the reverse direction on discharge.

This wattmeter, through a set of reducing gears, operates the dial pointer E (see Plate XLV), turning it in a clock-wise direction on discharge, and in the reverse direction on charge. The reducing gears are so proportioned that one complete charge or discharge of the battery will turn the dial pointer E through

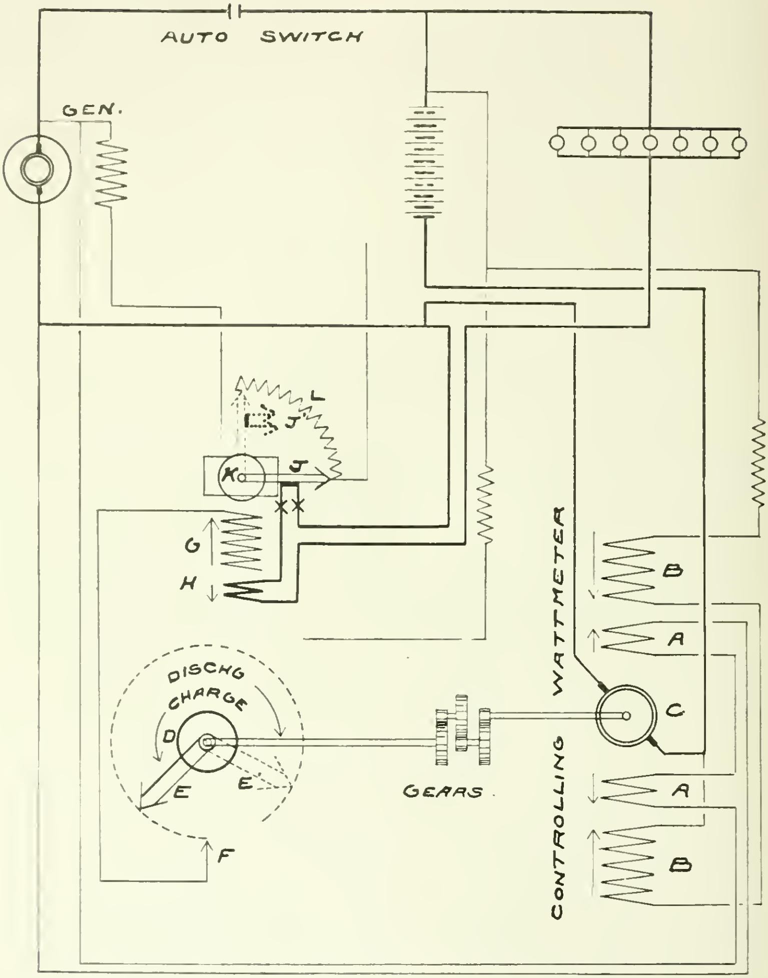

Plate XLV.—Wattmeter Control of Battery Charge.

slightly less than one revolution. The position of the dial also indicates the condition of the battery, it being in a position E^1 when the battery is completely discharged and as the battery becomes nearly charged may take a position at E. As the charge is continued to completion the pointer will be slowly moved toward the point F. Then when the battery is fully charged the pointer E will make contact with the contact point F.

This contact will complete the circuit through the coil G of the circuit breaker and trip the circuit breaker, causing the arm J to assume a position J^1. In doing this it automatically and slowly inserts the resistance L into the generator field circuit. This causes the generator voltage to fall below that of the battery and opens the automatic switch in the ordinary way. A glycerine check K is supplied which causes the arm J to move very slowly, thus insuring against a disadvantageous discharge upon opening or closing the generator field circuit. The whole equipment will now be inoperative all the rest of the day till the lights are turned on at night. In turning on the lights the porter pulls down the arm J, which also serves as a main switch in the lighting circuits, and restores normal operation of the equipment. It is impossible for the porter to obtain any light until he does pull down this arm J, so this part of the operation is entirely reliable.

The lamp current flowing through the differential coil H prevents the circuit breaker from opening when the lamps are turned on even though contact be made at the point EF, so that the night operation of the equipment is in no way interfered with even though a charged condition of the battery maintains.

In providing for low battery efficiency a differential winding A of the wattmeter fields is placed across the generator terminals, so that when the generator is operating and the battery is being charged the magnetic field within the wattmeter is of less intensity than when the generator is not operating and the coils B only are effective. This causes the meter to run slower on charge for an equal power consideration, the increase in speed being easily adjusted to care for any predetermined battery efficiency recommended by the manufacturers.

DISCUSSION

As mentioned above, the problem of automatically controlling the charge of a storage battery is a rather difficult one because of the peculiarly variable nature of the storage cell. There are a number of factors which alter the operation of a battery very materially and in fact it may be said that there is no function in the operation of a battery which is definite or even reliable where any degree of accuracy is desired.

In the first method of control mentioned, it is assumed that when a battery becomes fully charged, its voltage rises to some definite value at which point the controlling solenoid will operate. This, however, is not in accordance with the actual conditions of battery operation, for it cannot be said that a battery rises to any certain voltage when it becomes fully charged; this voltage at overcharge is dependent upon several factors, chief among which is the rate of charge, but even assuming that as normal there are other factors which very materially affect it. Variations in temperature and density of the electrolyte, and age of the elements, are factors which change the voltage at overcharge very considerably, so that instead of considering the voltage at overcharge as 2.6 volts per cell, with normal charging current flowing, we must consider it as varying from 2.5 to 2.65 volts per cell, depending upon the temperature and density of the electrolyte and age of the elements. Accordingly, any device depending upon this voltage for its operation, even though that apparatus itself be very sensitive and reliable, cannot operate with more than temporary success.

The second mentioned controller is based on a watt hour principle and depends, for its accurate operation, upon the assumption of a certain efficiency of operation of the battery.

This efficiency of operation, however, is not a definite value but is dependent upon several variable factors. It depends primarily upon the charge and discharge rates, and upon the charge and discharge intervals; that is, whether the battery is alternately on charge and discharge in rapid succession as in a floating battery, or whether it be completely charged and discharged over the entire range of its capacity. It is also somewhat affected by changes in temperature and density of the electrolyte, but these, however, only in so far as they affect the battery voltage.

In a comparison of these two methods of control it is readily apparent that neither one is exact or accurate because of the uncertainty of battery operation, but it must be said that while in the first controller mentioned, this inaccuracy may cause a complete failure in the operation of the device, for the voltage of the battery may never rise to that assumed value even though the battery is being overcharged, or on the other hand, it may rise to the assumed value before completion of charge, this is not so in the case of the second controller, for the probable error in adjustment may be easily compensated for by assuming the battery efficiency a trifle low and allowing a slight overcharge to occur. The control, however, is absolute and positive.

As far as the mechanical design and operation of the two devices are concerned, it may be said that they are both simple and reliable. It might seem as if a wattmeter were too delicate an instrument for this service, but it is to be noted that there are on the market at present, wattmeters of the mercury type which are of especially robust construction and which have given satisfactory service on electric railway cars.

In regard to the economic value of some such a protective device, attention should be called to the facts that no advantage comes from the power put into a battery after it has reached the fully charged condition, but that all such power is wasted, and that the depreciation of a storage battery in axle service is from 30 per cent. to 80 per cent. annually, depending upon the error of adjustment of the regulator. These facts are generally lost sight of by railroad electricians, who are satisfied if the battery is fully charged when it is needed, and who are content to include this high battery depreciation factor in that of the equipment as a whole, and consider this the price which they must pay for electric lighting. By the proper operation of a controlling device as described above, this battery depreciation could be reduced to 15 per cent. or 20 per cent. annually, thus effecting a saving which would in one year pay for such a device many times over, besides which, considerable saving of power would be effected.

Such a protective device would also render the operation of the axle equipment more reliable and satisfactory, for the regulator could then be set very high without fear of overcharging the battery and this would provide a speedy recovery of the battery in case it had become exhausted while in the station. In fact, it may be said that on many miscellaneous cars where it is impossible to determine the proper setting of the regulator, the use of some such a protective device is substantially essential to the continued successful operation of the equipment.

CHAPTER V

STORAGE BATTERIES AS APPLIED TO RAILWAY TRAIN LIGHTING

The storage battery has a very important function in the operation of electric lighting equipment on railway trains when acting either as an auxiliary to steam or axle driven generators or as the sole source of power as in straight storage equipments and devices. The storage battery is an expensive and delicate part of such an equipment and the cells require careful attention in order to secure satisfactory operation and to prevent rapid deterioration of the plates.

General Nature of the Storage Cell

The active constituents of a fully charged cell of the lead—lead type consist of peroxide of lead at the positive plates, spongy lead at the negative plates, and the electrolyte (a solution of sulphuric acid in water). During the discharge of the cell, the action is to convert both sets of plates, or electrodes as they are frequently called, into a soluble form of lead sulphate. During discharge the acid combines with the active portions of both plates forming this lead sulphate, which action changes the specific gravity of the electrolyte by removing a portion of the acid. During charging process these actions are reversed: the sulphate on the negative plate is reduced to spongy metallic lead, and that on the positive plate is oxidized to peroxide of lead.

It is to be noted that the sulphate of lead formed during the discharge of a cell is entirely different in its behavior from the white, hard, insoluble form which makes its appearance when a cell is carelessly managed and to which reference is hereinafter made.

The *electrolyte* is dilute sulphuric acid and may be prepared by diluting a suitable quantity of sulphuric acid with pure water. It is essential that both acid and water be free from impurities. Some impurities such as platinum, iron, copper, and many other metals even in minute quantities tend to cause self-discharge through local action, and lower the efficiency of the battery. Other impurities such as hydrochloric, nitric, and other acids tend to attack and to corrode the lead frame work which supports the active materials. It is, therefore, ordinarily recommended that all acid be purchased from the manufacturer of the battery. Any material obtained from other sources should be carefully tested before using. The purity of the water used for "flushing" the cells should also be carefully determined.

In this connection it is to be remembered that iron frame work or copper connections are attacked by the acid fumes, forming salts highly injurious to the cell if allowed to get into the electrolyte. All such connections to the frame work should be protected by reliable paint or varnish and should be washed occasionally.

The electrolyte used in storage cells has a specific gravity of about 1.2 and may be prepared by mixing one part by volume of sulphuric acid (1.84 Spec. Grav.) with five parts of water. The acid should be poured into the water, never the water into the acid. The acid must be poured into the water slowly and with caution to avoid a violent boiling and sputtering; this boiling hot acid will cause very painful and dangerous burns. The specific gravity should be determined only when the mixture is fully cooled. The prescriptions given by the manufacturers of storage cells of the proper acid gravity to be used in their cells vary somewhat, and the solution should be finally adjusted to the prescribed value by addition of acid or water.

Flushing Cells.—Due to the decomposition of the electrolyte and ordinary evaporation the water in the electrolyte is constantly depleted and must be replaced by fresh pure water, not acid. This in ordinary railroad work should be done every two weeks at least and in certain cases of overcharged batteries should receive more frequent attention.

On account of the loss of acid by the spraying which occurs at the end of the process of charging, and absorption of acid by the sediment, a gradual lowering of the acid gravity will occur. When on account of the above causes the acid density at the end of a full charge and at normal temperature has fallen 15 points (.015 in the gravity scale) below that normal value prescribed by the makers it should be brought up by the addition of acid.

Acid should never under any circumstances be added to a cell in which short circuits, high temperature, or partial charge may account for low gravity.

OPERATION OF BATTERIES

Charging.—The battery should preferably be charged at the normal rate prescribed by the maker. It is important that it should be given the proper amount of charge, and once a week a half hour's overcharge, using the normal current for charging, but excessive overcharging should be avoided as it will not only cause a rapid loss of electrolyte but will boil out the active material from the plates, thus greatly reducing their capacity and life.

The readings of the specific gravity of the electrolyte in one cell, or the voltage readings taken from time to time, may be used in following the charge. The specific gravity method is the more accurate as it is independent of the rate of charge, but in railroad work, due to the inaccessibility of the electrolyte, the less accurate but rough and ready method of voltage readings is relied upon. It must be remembered, however, that these voltage readings depend upon the rate of charging and in themselves are no indication of the state of charge unless the normal charging current is flowing. Open circuit voltage readings cannot be in any way relied on.

The normal rate is usually an eight hour rate, i. e., a rate which will give a complete discharge of the battery in eight hours. Thus for a 240 ampere hour battery the normal charging or discharging current would be 30 amperes. This rate should not be exceeded during the process of charging except for relatively short periods.

The voltage at the end of the charging process is not fixed, but varies as the battery gets older, due largely to an accumulation of insoluble lead sulphate in the active material. Therefore, a battery cannot be said with certainty to be fully charged when it has reached any definite voltage. This voltage at the end of the charging process may vary in new cells from 2.5 to 2.7 and in older cells may be as low as 2.4 when they are fully charged. However, a cell may be considered as charged when the voltage remains constant at approximately 2.5 volts per cell for a half an hour, with the normal charging current flowing.

Discharge.—The limit of proper discharge is reached when the voltage has fallen to 1.8 per cell with the normal current of discharge flowing. This is 28.8 volts on a 16 cell circuit, 57.6 volts on a 32 cell circuit, 90 volts on a 50 cell circuit, and 97.2 volts on a 54 cell circuit, and the batteries should not be discharged below these points.

The rate of discharge and charge should always be within the limits prescribed by the manufacturer. The cells should be carefully inspected and cared for according to the directions of the manufacturer in order that their life may be reasonably long.

An overcharge of a half an hour at the normal rate once a week is a very good thing for any battery in that it tends to prevent formation of the insoluble white sulphate; but such a continued overcharge as was found in tests of many of the axle equipments, is sure to cause a rapid destruction of both positive and negative plates. This is caused largely by the boiling action of the gases mechanically removing the active material of the plates, which collects as sediment in the bottom of the cells. This sediment is not dust nor cinders nor scale nor useless refuse of dead material but is the very life and capacity of the battery itself, so that the depreciation of the battery is, in one direction at least, expressed by the depth of sediment in the bottom of the jars.

Battery Box.—That the temperature may be moderate during summer months and the air dry, the battery compartment must be ventilated. This is also very essential to remove the explosive mixture of oxygen and hydrogen formed during the process of charging the battery.

The importance of the latter is not generally recognized but may be shown by citing a news article in the *Railway Gazette,* 1900, p. 681, which describes a violent explosion under a dining car, which was caused by the collection of oxygen and hydrogen from the cells, this explosive mixture being ignited by an electric spark on a loose connector. Such an accident might easily riddle the battery box and not only cause the total loss of the battery but might be a source of fright and danger to the traveling public. This can easily be remedied by boring a few small holes in each end of the battery box.

To properly preserve the woodwork, particularly the trays and lead lined wooden tanks and also the whole interior of the battery box, care must be taken to keep these parts well protected with a heavy paint which is not subject to the attack of sulphuric acid, preferably one of an asphaltum base.

Cell Tanks or Jars.—A cell tank or jar of special type must be used to withstand the severe conditions of railway operation. In general there are two types which are suitable: lead lined wooden tanks and hard rubber jars set in wooden trays.

The lead lined tank is more expensive, but is without doubt the more reliable and satisfactory. It consists of a heavy oak box of solid construction lined with sheet lead with joints burned to make them water tight; then, to prevent this lead lining from short circuiting the plates, heavy glass plates are fitted inside this lead lining so as to completely cover it. A lead lined cover is bolted over the top of each compartment.

The rubber jar is much cheaper and of more simple construction. It is simply a hard rubber reinforced jar set in a wooden tray, usually in sets of two as illustrated in Plate XXV. A tight fitting rubber cover is also provided to prevent the slopping of acid. This is hardly as satisfactory a jar as the lead lined tank, as it is often cracked or broken, allowing the electrolyte to leak out, thus completely crippling the battery. However, in case of a lead lined tank care must be taken to prevent grounds and moisture in the wooden container else electrolysis is apt to eat holes in the lead lining and have the same result as a broken rubber jar.

Hard rubber covers are supplied in connection with hard rubber jars, these fitting more or less tightly to protect the plates from dust but at the same time permitting their easy removal for inspection of the plates.

The relative weights of a pair of cells complete of 240 ampere hour capacity of the same type plates in these two types of jars are roughly 200 lbs. in hard rubber and 300 lbs. in lead lined tanks. The relative costs of the tanks alone are roughly $15 for two hard rubber jars and wooden tray, and $24 for a lead lined double compartment tank.

The *connectors* generally used each consist of a rubber covered flexible copper wire with lead lugs burned on the ends. These lugs of lead should be cast so as to completely protect the copper wire from the acid.

CHAPTER VI

COMPARISON OF THE VARIOUS METHODS OF RAILWAY CAR LIGHTING

As in the operation of a train the first essential is to get the train over the road on time and with safety, so in lighting the train the first essential is to have good light all the time, and to do so without jeopardizing the safety of the travelling public. The question of efficiency of operation of a railway car lighting equipment is not only the ratio of power output to intake, but a vast number of other considerations enter into the problem, till the mere machine efficiency or cost of operation becomes of secondary importance.

In considering all the various methods of electric lighting a railway car from a comparative point of view, it must be said that it is impossible to make a sweeping claim of superiority for any one type of equipment. All the equipments operated have certain advantages and certain disadvantages which render each equipment more or less applicable to certain kinds of service. It may also be said that the success of any of the types of lighting equipment lies largely in the hands of the railway operating department.

There are, however, certain features in the operation of the various types of equipment which should be considered in a comparative way.

The simplest of all the electrical equipments used is undoubtedly the straight storage equipment. This, however, has the disadvantage that it requires expensive charging stations at the terminals, by which the batteries are charged each day. This equipment is not applicable to long runs overland, but is most

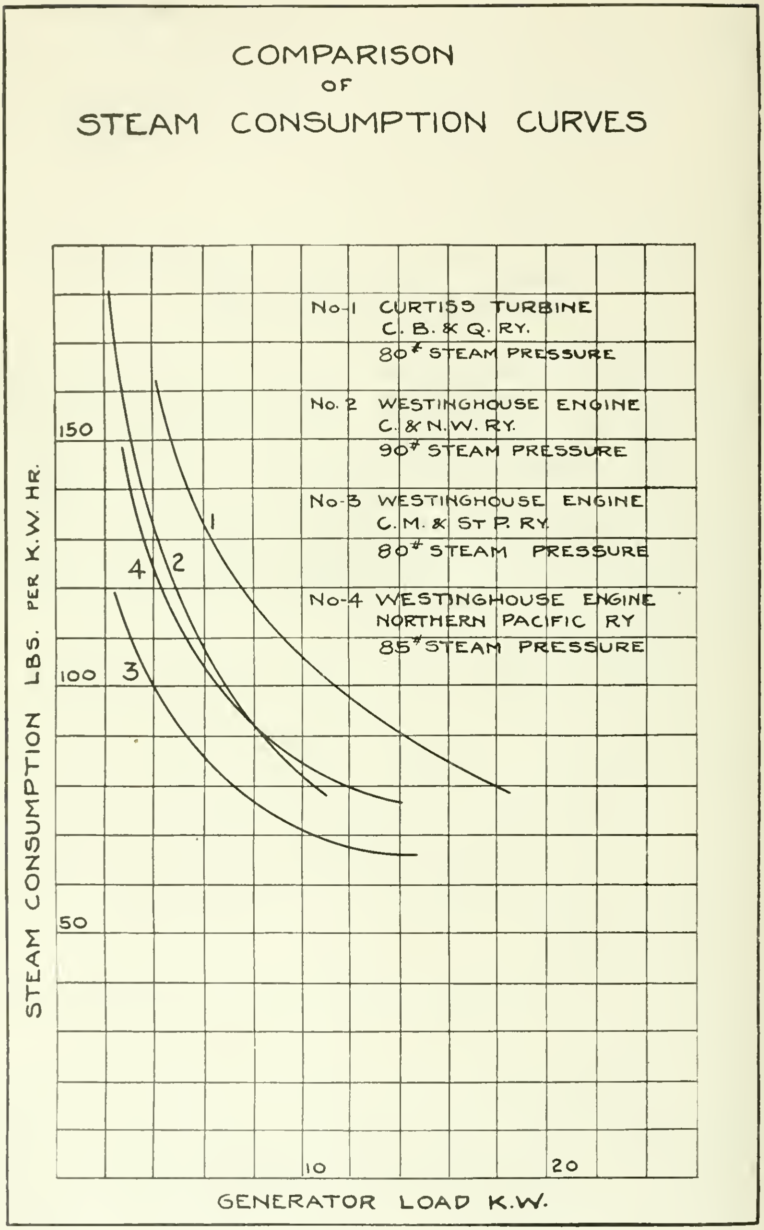

Plate XLVI.—Showing Comparison of Steam Consumption of Various Equipments.

economically operated on short runs where there is heavy traffic and a large number of cars are equipped.

The steam-driven generators are undoubtedly next in the order of simplicity. They, however, have a disadvantage in that they require an attendant. The C., M. & St. P. Ry. and C. & N. W. Ry. have largely overcome this objection by educating their baggagemen to operate the engine sets in addition to their regular duties. Another disadvantage of the system is that the train must be operated as a unit, and will not permit any car not properly wired to be inserted in the train. It is obvious that this type of equipment is most applicable to trunk line trains having a certain definite run, and especially to the overland trains.

The axle equipments have the disadvantage of complexity and high depreciation, but on the other hand they provide that each car is an independent unit, which makes this method of lighting a flexible one which is applicable to cars on miscellaneous runs as well as those in block trains. In fact, it may be said that there are a large number of cars for which this is the only suitable method of lighting by electricity.

The proper operation of axle equipments, however, is such an intricate one that any railroad deciding to enter the field of axle lighting should place a man at the head of that department who has a clear conception of all the theoretical considerations underlying the operation of these equipments and at the same time has a good practical knowledge of storage battery operation. Then that railroad may feel safe in the expenditure of money for such equipment and have every reason to expect a satisfactory and economical return in the method of lighting its cars by electricity. Where a railroad buys a few axle equipments, however, and places them in operation on its cars as a trial, expecting them to care for themselves to a large extent, such an experiment is sure to result in failure and dissatisfaction and a misconception of the real merits of the equipments.

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TESTS ON PLAIN AND REINFORCED CONCRETE COLUMNS

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TESTS ON PLAIN AND REINFORCED CONCRETE COLUMNS

I. INTRODUCTION

The present bulletin reports tests on plain and reinforced concrete columns made in the laboratory for testing materials at the University of Wisconsin during the summer of 1908. The purpose of these tests was to study the elastic properties and strengths of some of the most common types of columns used in concrete construction. The following five types were tested: 1, plain concrete columns; 2, columns reinforced with latticed angle structural steel columns; 3, columns reinforced with high carbon steel wire spirals; 4, columns reinforced with spirals and longitudinal mild steel rods; 5, columns reinforced with longitudinal mild steel rods. The tests were of a preliminary nature to determine the type of column upon which further investigations could most profitably be made.

All reinforced columns were made with a protective shell of concrete one or two inches thick on the outside of the steel. While this made it difficult to study the distribution of stress in the concrete and reinforcing steel, useful information was obtained in regard to the behavior of this shell. No attempt is made to derive any formula based on so few results for any one type of column. It will be noted, however, that the results for any one series of columns are in general of sufficient number and uniformity to be representative for the percentage of reinforcement used.

Neither the stresses nor the factors of safety used in Tables VIII, IX or X are intended as a basis for design. They are put in only for the purpose of comparing the different types of columns. More reliable data is needed before the proper working stresses and the necessary percentage of lateral and longitudinal reinforcement can be stated.

Due acknowledgement is hereby made to Dean F. E. Turneaure and Professor E. R. Maurer for valued suggestions received in making and reporting these tests and to F. M. McCullough and A. H. Miller, members of the mechanics department, for assistance in performing the same. E. D. Gilman of the class of 1910 prepared the drawings for the bulletin. The spirals used in these tests were generously contributed by the "American System of Reinforcing for Concrete Construction" of Chicago. Dean Turneaure donated the structural steel columns.

II. MATERIALS

Cement. Atlas portland cement from Hannibal, Missouri, purchased in local market, was used in these experiments. Table I gives the tensile strengths of neat and 1:3 mortar briquettes tested at 7, 28 and 60 days.

TABLE I.

Tensile Strength of Cement.

Briquette Number.	Ultimate strength in lbs / in^2.					
	Age 7 days.		Age 28 days.		Age 60 days.	
	Neat.	1:3 Mortar.	Neat.	1:3 Mortar.	Neat.	1:3 Mortar.
1	542	260	722	284	660	340
2	442	218	664	352	650	334
3	484	272	570	280	690	350
4	442	220	650	368	700	
Average	478	243	652	321	675	341

Sand. A local bank furnished a rather fine but fairly clean sand. The mechanical analysis of this sand is contained in Table II.

TABLE II.

ANALYSIS OF SAND.
PER CENT. VOIDS = 37. WT. PER CU. FT. = 91.5 LBS.

Sieve No.	Diameter of mesh.	Per cent. passing.
¼	.25	100
6	.131	99.5
10	.073	94.3
16	.042	87.5
20	.034	83.9
30	.022	70.0
40	.015	58.0
50	.011	26.0
74	.0078	19.5
100	.0045	6.7

Stone. A soft crushed limestone was secured from a near-by pit. This stone crushed into rough surfaced prisms to which the mortar strongly adhered. A mechanical analysis of the stone is found in Table III.

TABLE III.

ANALYSIS OF LOCAL LIMESTONE.
PER CENT. VOIDS = 43.5. WT. PER CU. FT. = 90.5 LBS.

Diameter of mesh. Inches.	Amount retained. lbs.	Per cent passing
1.25	0.	100
1.00	1.0	97.6
.75	2.5	91.6
.50	15.0	55.6
.33	11.0	29.4
.25	2.25	25.0
.14	4.5	13.2
Residue	5.5	10.8

Concrete. A 1:2:4 mix of cement, sand and stone was used in making all specimens. Proportioning was performed by weighing the required volumes, the cement being assumed to weigh 100 pounds per cubic foot. The specific weights of the sand and stone used are given in Tables II and III. All concrete was mixed in a No. 0 Smith batch mixer which has a capacity of 6 cubic feet of concrete and a speed of about 25 revolutions per minute. In mixing, the sand was first thrown into the mixer; cement was then put in and the dry mixture of sand and cement given about a half dozen turns. Half of the stone was next placed in the mixer and the water turned on. When about half of the water had run in, the remainder of the stone was added. Mixing was continued for one minute after the required amount of water had been added. The total time of mixing from the putting in of sand until the discharge of the batch was about three and one-half minutes. A gravity water-feed discharging from a calibrated tank through $^3/_4$-inch pipes into the mouth and hopper of the mixer afforded a satisfactory method of measuring the amount of water required for the batch. The quantity of water necessary to procure a wet concrete, which would flow readily about the reinforcement without much puddling, varied from 9½ to 10 per cent. of the weight of the sand, cement and stone. This variation was caused mainly by the change, from time to time, in the moisture content of the sand. The good quality of the concrete in the specimens was undoubtedly due in a large measure to the thorough mixing of all the materials. The way in which the water was added played an important part in securing a uniform consistency throughout the batch.

Steel. The structural steel reinforcement for the columns of Series B was purchased from the Wisconsin Bridge and Iron Company of Milwaukee. The mild steel rods used were bought in the local market. The "American System of Reinforcing for Concrete Construction" of Chicago donated the spirals for the columns of Series C and D.

The tensile yield point and ultimate strength of the steel angles used in the columns of Series B were about 51.000 lbs/in^2 and 82.000 lbs/in^2 respectively. These values were determined from a couple of $\frac{3}{4}$x$\frac{3}{16}$-inch pieces sawed from an uninjured portion of the steel column BS after it was tested. Table IV shows that the yield points of the $\frac{5}{8}$-inch, $\frac{1}{4}$-inch mild steel and $\frac{1}{4}$-inch high carbon steel rods were 42.000. 47,000 and 98.000 lbs/in^2 respectively. Their corresponding ultimate strengths were 61.000, 62.000, and 130.000 lbs/in^2 respectively.

TABLE IV.

Tension Tests of Steel Used in Columns.

Size of Bar ins.	Area sq. in.	Load at Yield Point lbs.	Maximum Load lbs.	Stress at Yield Point lbs/in.^{2}	Ultimate Strength lbs/in.^{2}
.627	.309	12.760	19.025	41.300	61,600
.626	.308	13.000	19.375	42.200	62,700
.626	.308	13,500	19,725	43,800	64,000
.628	.310	12.975	19.430	41.800	62,600
.626	.308	12,485	18,025	40.400	58.500
.627	.309	12.330	18,000	39,900	58.200
			Average	41.570	61.270
.258	.052	2.450	3.220	46.900	61,800
.256	.051	2.460	3.215	47.900	62,300
			Average	47.400	62,050

High Carbon Steel Wire.

.254	.051	4.950	6.600	97.700	130,000

III. SPECIMENS—MAKING, CURING AND TESTING

Auxiliary Specimens. From every batch of concrete one 6x8-inch cylinder was made. Tests of these cylinders served as an index of the strength of the concrete in the different columns. Table V gives the data for these auxiliary test pieces. The cylinders are designated by a letter and two numbers as A11, A12, etc. The letter and first number indicate the column in which the same concrete was used, while the second number tells in what part of the column the concrete was placed. Thus, A11, A12, A13 signify that the cylinders were made from the same batches that were poured into the bottom, middle portion, and top of column A1, respectively. The cylinders were left in the molds 6 days and then stored under the same conditions as the columns.

TABLE V.

Compressive Strength of Six-Inch Cylinders.

1 : 2 : 4 Concrete.

Col.	Specimens 6x18 in. cylinders.	Age in days.	Specific weight lbs/ft.^{3}	Modulus of elasticity at $\frac{1}{3}$ ult. strength lbs/in.^{2}	Ultimate strength lbs/in.^{2}
A1	A11	63	145	3,000,000	3,140
A1	A12	63	141	2,700,000	1,890
A1	A13	63	140	....	2,250
A2	A21	63	143	2,600,000	2,320
A2	A22	63	140	....	2,470
A3	A31	62	141	2.600.000	2,140
A3	A32	62	141	....	2.340
A4	A41	62	141	2.800.000	2,380
A4	A42	62	142	....	2,340
B1	B11	62	142	2,700,000	2,330
B1	B12	62	142	....	2,210
B2	B22	62	142	2,800,000	2,760
B2	B23	62	144	....	2.520
B3	B31	62	143	3.000.000	2,420
B3	B32	61	143	....	1,990
B4	B41	62	141	....	2,030
B4	B42	62	142	....	2,250
C1	C11	63	140	3.100,000	2,100
C1&2	C12	63	142	3.200.000	2.460
C2	C22	61	139	....	1.920
C3	C31	63	143	3,300,000	2,010
C3	C32	63	141	3.300.000	2,360
C4	C42	62	140	....	2.340
C4	C43	62	139	....	1,960
D1	D11	56	143	2.900.000	2,080
D1&2	D12	56	142	3,400,000	2,220
D2	D22	56	142	....	2,040
D3	D31	56	144	3.100,000	2,480
D3	D32	56	143	3.100,000	2,280
D4	D42	56	143	....	2,250
D4	D43	56	145	....	2,460
E1&2	E12	55	143	3,200,000	2,430
E3	E32	54	142	....	2,040
F1	F11	63	....	....	2,480
F1	F12	63	....	....	1,990

Columns. All columns of a series were made on the same day. Much care was taken to keep the conditions governing the making of the columns uniform for all series. The properties of the columns tested are given in Table VI. All columns were 10 ft. long.

The four plain concrete columns of Series A were 12 in. square. Column F1, also unreinforced, was 8 in. square.

Each column of Series B was reinforced with a built up steel column, shown in Fig. 1, which weighed about 250 pounds. The columns of this series had a shell of concrete 2 in. thick outside of the steel reinforcement, making their cross-sectional dimensions 12x12 in. Before testing columns B1 and B4

TABLE VI.

PROPERTIES OF COLUMNS TESTED.

All colums 10 ft. high. 1:2:4 concrete.

Col.	Reinforcement Kind.	*Per cent. Vertical.	 Lateral.	Shape.	Area Sq. in.	Age at test days.
A1	....	0	0	Square.	144	65
A2	....	0	0	..	143	63
A3	....	0	0	..	142	64
A4	....	0	0	..	141	65
B1	4. 2x2x3 16-in latticed angles.	4.5		..	64	64
B2		2.02		..	142.5	62
B3		2.01		..	143	61
B4		4.5		..	64	63
C1	¼-in. high carbon steel spiral. 10-in. diam., 1-in. pitch.	0	1.33	Octagonal.	118	62
C2		0	1.33	..	118	62
C3		0	2.00	Round.	78.5	64
C4		0	1.33	Octagonal.	118	65
D1	9. ⅝-in. round mild steel rods and ¼-in. high carbon steel spiral. 10-in. diam. 1-in. pitch	2.35	1.33	..	118	58
D2		2.35	1.33	..	118	60
D3		2.35	1.33	..	118	61
D4		2.35	1.33	..	118	62
E1	9. ⅝-in. round mild steel rods with ¼-in ties. 1 ft. c. to c.	2.35	0.11	..	118	55
E2		2.35	0.11	..	118	57
E3		2.35	0.11	..	118	57
F1	....	0	0	Square.	64	63
Bs	Latticed angle steel column reinforcement in Series B.					

* Percentages are computed for total cross-section.

this outside shell was knocked off, making their cross-section 8x8 in. In Table VI no attempt has been made to figure the percentage of lateral reinforcement in these columns, although the lacing bars and angles unquestionably produced considerable lateral restraint on the concrete core.

Columns of Series C were octagonal in cross-section with an inside diameter of 12 in. They were reinforced with spirals 10 in. in diameter composed of ¼-in. wire with a 1-inch pitch. Three longitudinal crimped spacing bars served to maintain a uniform pitch. These spirals weighed about 63 pounds each. Fig. 2 (a) shows how their reinforcement was made up. Column C3 was stripped of its outside shell before testing, thus making its cross-section a circle 10 in. in diameter.

Fig. 2 (b) shows the same spiral as used in Series C, fitted with 9 ⅝-in. round rods to serve as reinforcement for the columns Series D. The diameter of the No. 16 wire used in tying the vertical rods to the spiral was .077 of an inch. All longi-

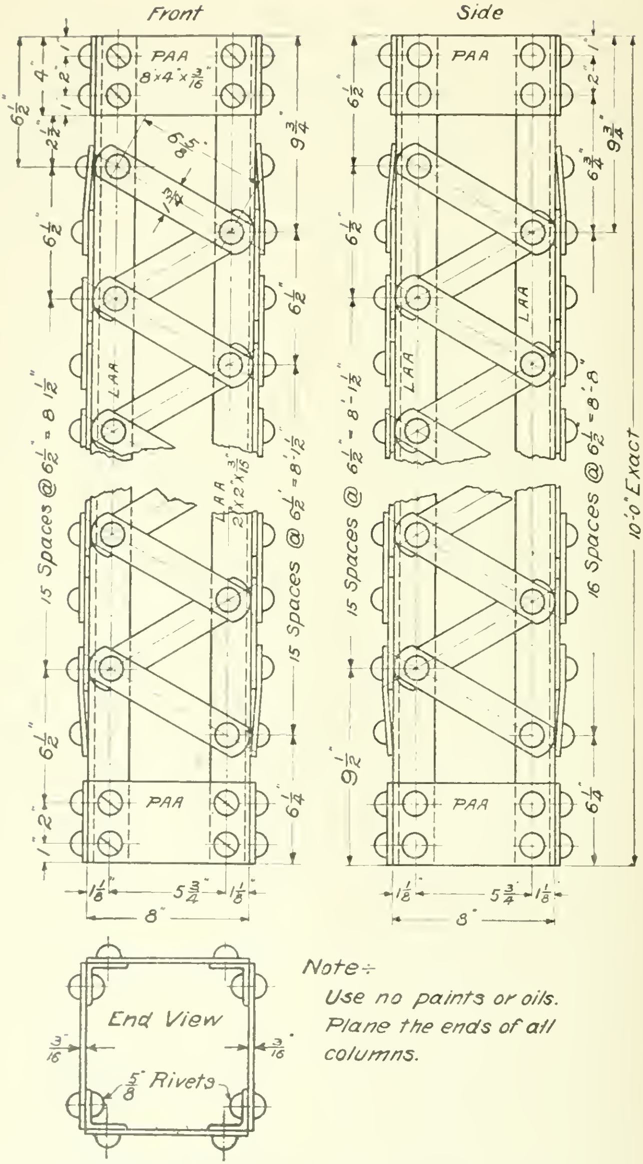

Fig. 1.—Reinforcement Used in Columns of Series B.

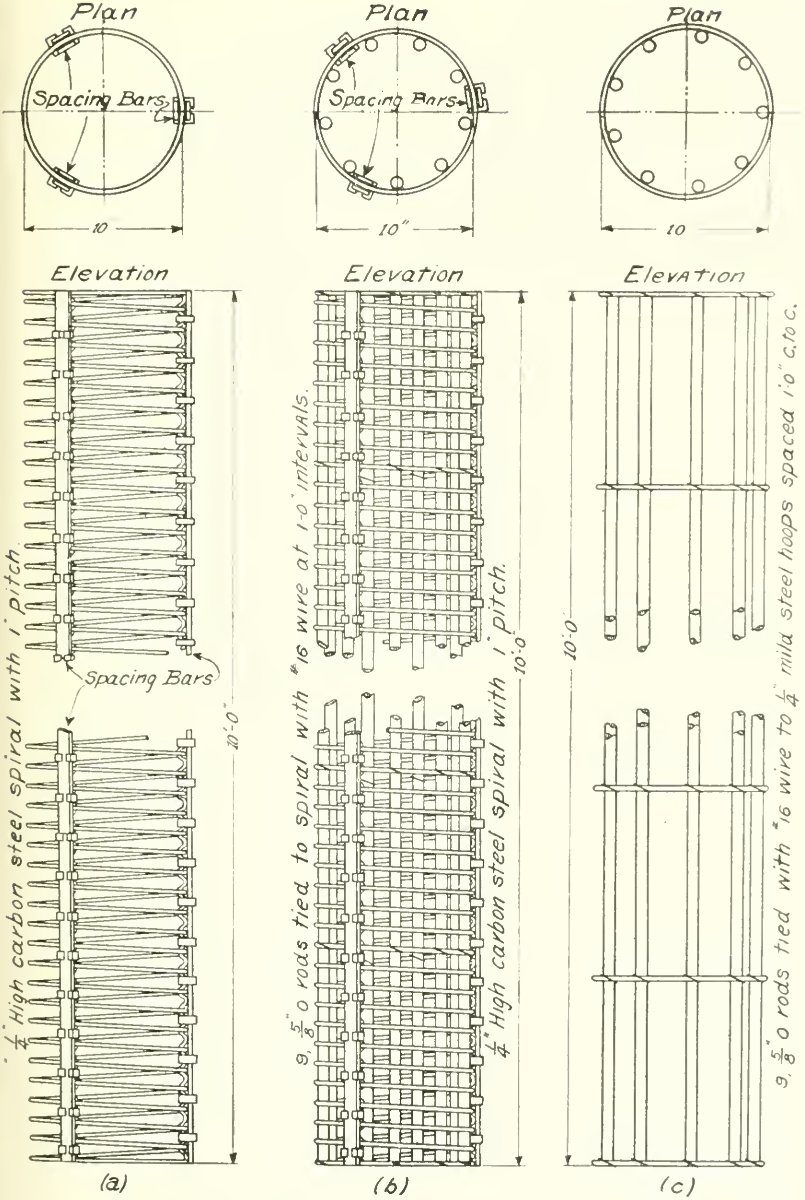
Plan
Spacing Bars
10
Elevation
Spacing Bars
10'-0"
¼" High carbon steel spiral with 1" pitch
(a)
Plan
Spacing Bars
10"
Elevation
9, ⅝" o rods tied to spiral with #16 wire at 1-0" intervals.
¼" High carbon steel spiral with 1" pitch.
10'-0"
(b)
Plan
10
Elevation
10'-0"
9, ⅝" o rods tied with #16 wire to ¼" mild steel hoops spaced 1'0" c. to c.
(c)

Fig. 2.—Reinforcement Used in Columns of Series C, D and E.

tudinal rods in the columns were milled to the same length. This was done so that the bed plates would bear on all rods alike when the columns were tested. The weight of this form of reinforcement was about 160 pounds per column.

The reinforcement used in the columns of Series E is shown in Fig. 2 (e). The longitudinal rods in this series were also milled to exact length and spaced uniformly around the inner side of the ¼-in. hoops. These hoops were 10 inches in diameter and placed 1 foot apart. This reinforcement weighed about 103 pounds per column. Column BS was a structural steel column like those used in reinforcing Series B.

Forms. Fig. 3 shows the type of wooden form used in molding the columns. The dotted lines in the plan indicate the triangle pieces which were placed in the corners of the molds to make the octagonal columns. These molds were set upon planed cast iron bed plates which were carefully leveled before columns were poured. The six-inch cylinders were made in cast iron molds set upon a leveled steel plate.

Making. About 5½ cu. ft. of concrete was made in a batch so that two batches were required for a column and the accompanying cylinders. In making the plain columns the forms were built up in three sections. As soon as one section was filled and puddled the next above was fastened in place and filled. In fabricating the other columns the whole form was set up and the reinforcement held in position while the concrete was poured in from a pail at the top. While a column was being poured the concrete was continually puddled with a rod, both inside and outside of the reinforcement to prevent the formation of pockets and air holes. After a mold was filled it was lined up with a plumb bob by driving wedges under the base plate. A day or two after columns were made, a thin coat of 1:1 mortar was applied to their tops. While the mortar top was still soft a cast iron bed plate was placed upon it and carefully leveled. The depth of the coating over the ends of the rods or angles in the reinforcement was never greater than $\frac{1}{32}$-in. In making the columns of Series C considerable difficulty was experienced in keeping the flexible spirals in the center of the molds.

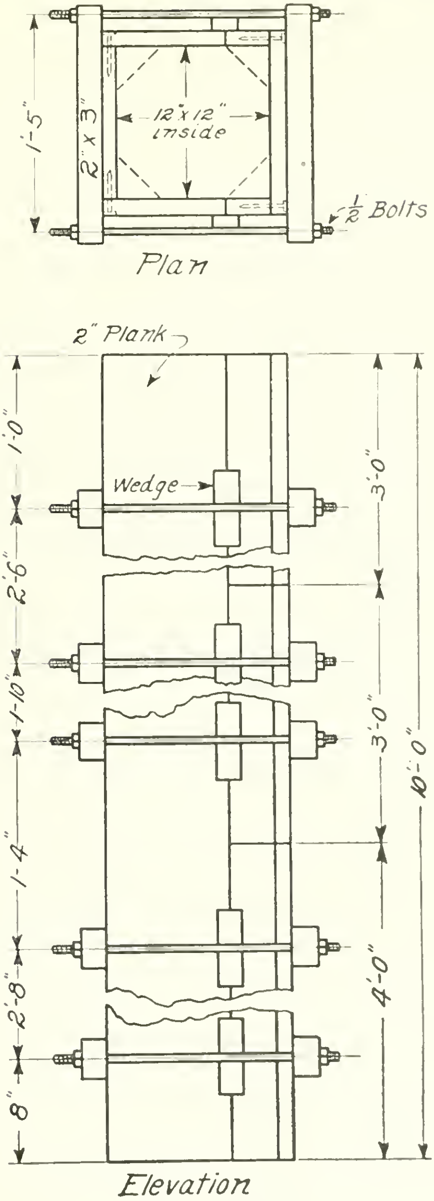
1'-5"
2"x 3"
12"x 12"
inside
½ Bolts
Plan
2" Plank
Wedge
1'-0"
2'-6"
1'-10"
1'-4"
2'-8"
8"
3'-0"
3'-0"
4'-0"
10'-0"
Elevation

FIG. 3.—FORMS.

Curing. Forms were removed from the columns at the end of six days. The columns were then wet twice a day for one week, after which they were allowed to cure in the air of the laboratory. The temperature of the room varied from 70° to 85° F.

Testing. About two months after the columns were made they were tested in the 600,000 pound vertical hydraulic testing machine in the laboratory. The lower head of this machine is rigidly fixed to the piston rod of a hydraulic jack, while the upper head is free to adjust itself to a specimen through a ball and socket joint. A column was put in the machine and bedded on a cast iron plate at the top and bottom, a sheet of blotting paper being placed on either end of the test piece to fill up any slight inequalities in the bearing surface. If the column was not plumb it was made so by placing iron shims under the lower bed plate. The columns were loaded at the rate of approximately 200 lbs/in^2 per min. Loads were applied in increments of 15,000 pounds. The cylinders were tested in a 100,000 pound Riehlé universal testing machine.

Measurements of the longitudinal deformations were made by means of copper wire dial compressometers, which measured to .0001 of an inch. Four frames were fastened to the column, two about 20 ins. from its top and two about the same distance from its base. Two dials were placed on the top frames and two on the lower frames in such a manner that there was a dial on each of four sides of the column. A No. 36 covered copper wire leading vertically to and around each dial drum from a pin on the lower or upper frame, depending upon the position of the dial, and held taut by a small weight imparted motion to the dial drum. Thus deformations over a gage length of 80 inches were measured on all four sides of the column. Readings corresponding to a given load were taken after the motion of the dial pointers had ceased.

To measure deflections a couple of thread, scale and mirror devices similar to those used in measuring the deflection of beams (See Series of 1906) were employed. These were placed so as to measure the deflection of the column in planes at right angles to each other. The readings of these deflections were used as a check upon the compressometer readings.

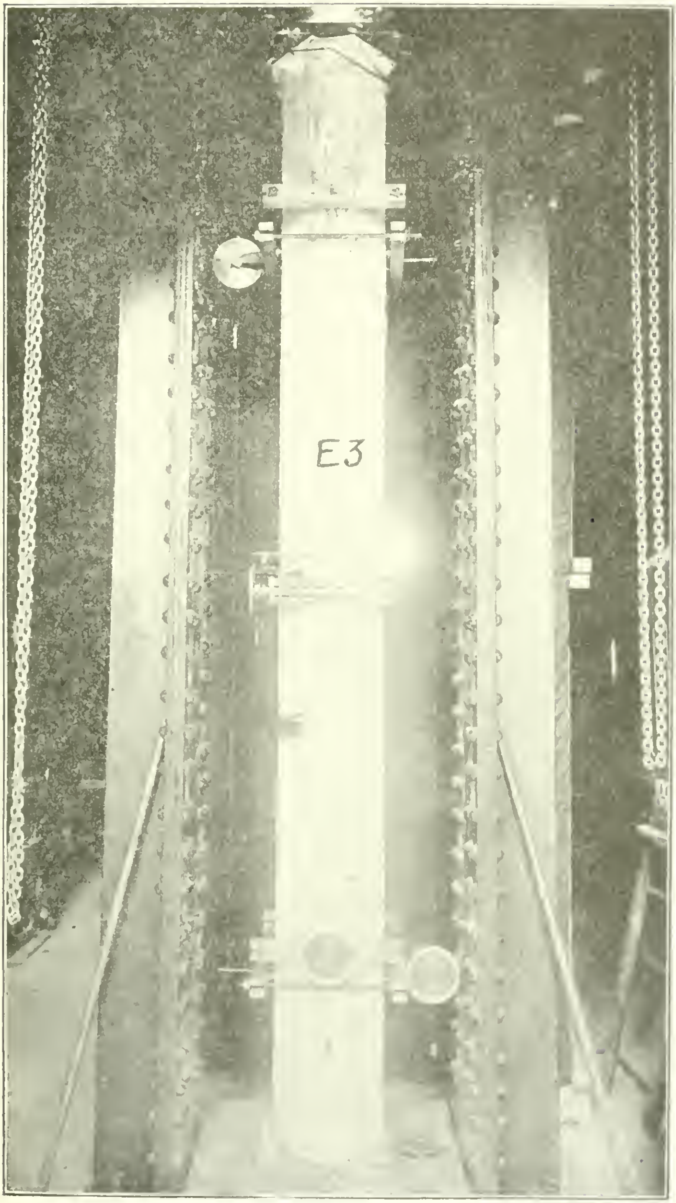

PLATE I.—COLUMN E3 READY TO BE TESTED.

An attempt was made to measure lateral deformations, but owing to a lack of rigidity in the apparatus used the values are not considered trustworthy and will not be reported. Plate I shows column E3 fitted with apparatus in position ready to be tested.

The moduli of elasticity of cylinders were determined by the dial compressometer shown in the bulletins, Series 1906 and 1907. This apparatus measures the sum of the deformations on two opposite sides of a cylinder. Consequently the moduli of elasticity of the cylinders were not determined with the same degree of accuracy as that of the columns where the deformations were measured on four sides.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

1. Tests of Auxiliary Cylinders

Table V contains the results of compression tests made on the six-inch cylinders. The modulus of elasticity at one-third the ultimate load for these cylinders averages 3,000,000 lbs/in², and the ultimate strength 2,275 lbs/in². The maximum variation in strength on either side of the mean, with the exception of A11, which was abnormally strong, is about 16 per cent.

A comparison of theoretical interest is given in Fig. 4. This diagram shows the average stress deformation curve, for the cylinders upon which deformations were measured, and a theoretical parabola which best fits the plotted points. The general equation of this parabola is

$$f'_c = f_c \left[2\frac{\varepsilon'}{\varepsilon} - \left(\frac{\varepsilon'}{\varepsilon}\right)^2\right],$$

Where f'_c = any unit stress (lbs/in²)
f_c = ultimate strength (lbs/in²)
ε' = unit deformation corresponding to f'_c;
ε = unit deformation corresponding to f_c.

For these tests this equation reduces to

$$f'_c = 2360\left[\frac{2\varepsilon'}{.0015} - \left(\frac{\varepsilon'}{.0015}\right)^2\right]$$

The close agreement between the two curves indicates that a parabolic curve well represents the stress-deformation curve for this grade of concrete.

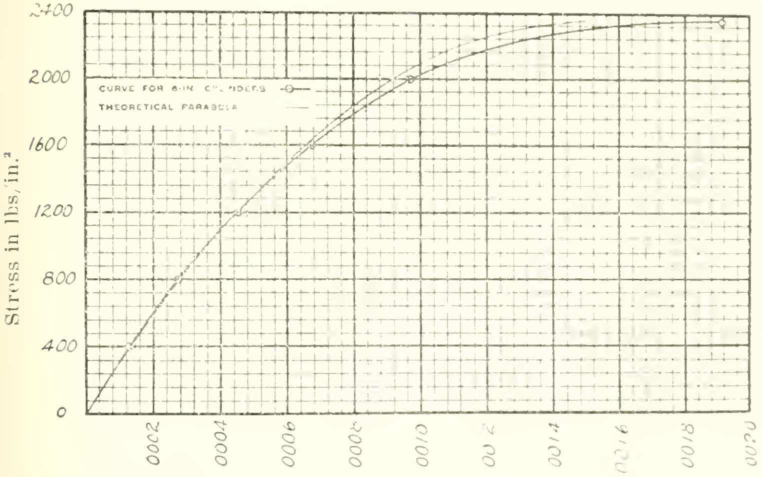

FIG. 4. STRESS-DEFORMATION CURVE OF CYLINDERS COMPARED TO A THEORETICAL PARABOLA.

2. SERIES A

The four 12 x 12 in. plain concrete columns of this series broke at an average stress of approximately 2,070 lbs/in^2, the maximum variation of a single result from this mean value being only 40 lbs/in^2, or 2 per cent. Columns A1 and A4 failed suddenly by shearing off on inclined planes. In the tests of A2 and A3, the outside of the column fell away, leaving two conical frustrums with their apexes together. As far as could be observed, no failure took place due to poor end bearings. The concrete in all of these columns presented a good homogeneous appearance. Many of the stones were sheared off at failure and but few air pockets showed at the broken sections. The character of failure as well as the ultimate strengths indicate a high degree of uniformity in the test pieces.

The moduli of elasticity and ultimate strengths for these col-

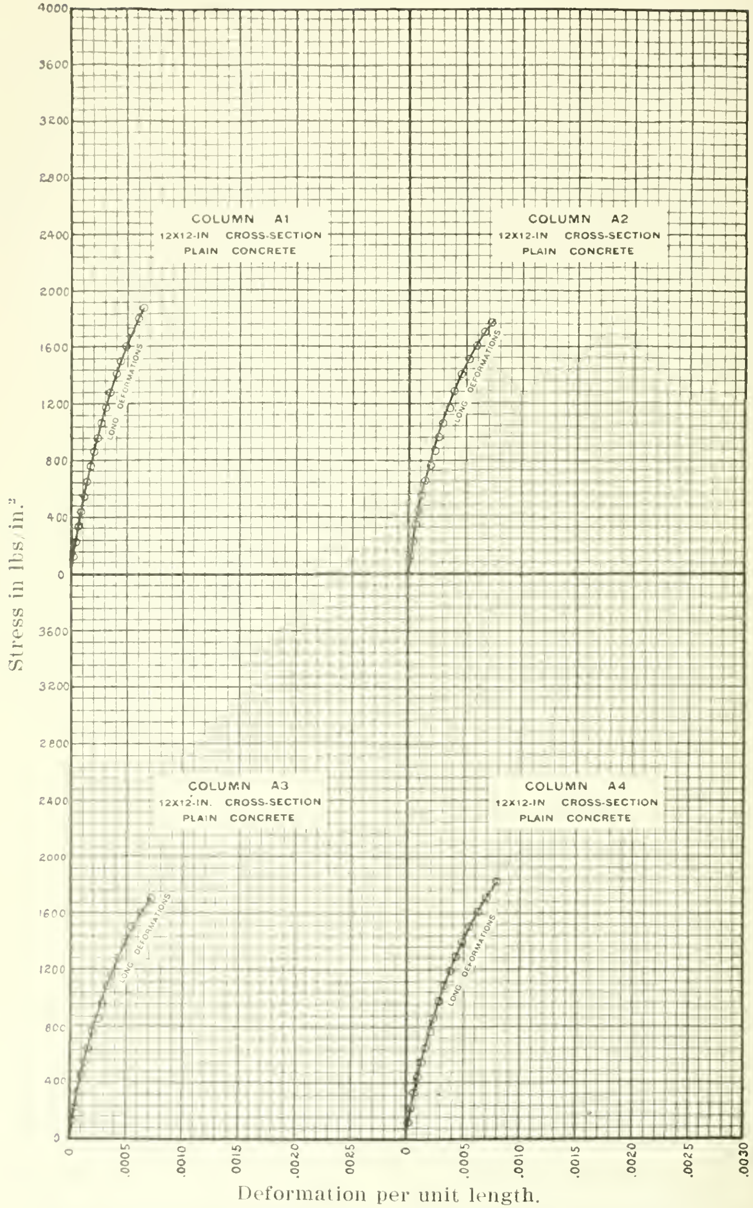

FIG. 5.—STRESS-DEFORMATION CURVES FOR COLUMNS OF SERIES A.

umns are given in Table VII. Values of the modulus have been computed at one-third of the ultimate strength by dividing the unit stress at this point by the corresponding unit deformation. It will be observed that the modulus for these plain columns is considerably larger than that obtained for the corresponding six-inch cylinders in Table VII, or the columns of Series C, and somewhat larger than that obtained for the columns with longitudinal reinforcement. This increased stiffness was probably caused by the greater density of the columns of Series A.

The stress deformation curves for this series are contained in Fig. 5. In order that the apparatus might not be injured, it was necessary to remove it before the ultimate load was reached. Consequently the full stress deformation curves are not given in the figure.

TABLE VII.

STRENGTH AND MODULI OF ELASTICITY OF COLUMNS TESTED.

1:2:4 Concrete. Age 2 months.

Col. No.	Reinforcement.		Modulus of elasticity at ⅓ max. load.	Maximum load lbs. (P)	Ultimate strength lbs in²*
	Percent. vertical.	Percent. lateral.			
A1	....	....	4,000,000	291,000	2,040
A2	....	....	4,000,000	303,000	2,110
A3	....	....	3,840,000	292,000	2,055
A4	....	....	3,600,000	294,000	2,080
F1	....	....	3,800,000	120,600	1,880
+B1	4.5	....	4,200,000	237,000	3,710
+B4	4.5	....	4,000,000	242,000	3,780
B2	2.0	....	3,500,000	303,000	2,125
B3	2.0	....	3,400,000	288,000	2,015
C1	....	1.33	2,400,000	366,000	4,660
C2	....	1.33	2,100,000	345,000	4,390
+C3	....	2.00	1,700,000	288,000	3,660
C4	....	1.33	2,500,000	268,000	3,440
D1	2.35	1.33	3,200,000	351,000	4,470
D2	2.35	1.33	3,100,000	330,000	4,200
D3	2.35	1.33	3,200,000	391,000	4,970
D4	2.35	1.33	2,830,000	421,000	5,360
E1	2.35	0.11	3,800,000	273,000	2,310
E2	2.35	0.11	3,700,000	273,000	2,310
E3	2.35	0.11	3,800,000	318,000	2,695

*Ultimate strengths for series C and D $= \frac{\text{maximum load.}}{\text{core area.}}$

+Protective shell removed

3. Series B

These columns were all made 12 x 12 in. in cross-section and reinforced with structural steel columns like the one shown in Fig. 1. This type of column when tested showed considerably more toughness than did the plain columns. Columns B2 and B3 were tested as made. Shortly after the deformation in these columns indicated that the elastic limit of the steel had been reached, or at about the ultimate deformation which a plain concrete column would stand, the two-inch protective became badly cracked and small particles of concrete began to fall off. Very soon after, the maximum load was reached and large sections of the protective shell fell off accompanied by a decided decrease in load. The ultimate loads and ultimate strengths, figured on gross cross-section, were no larger than those obtained for the plain concrete columns of Series A. At first glance these figures seem to indicate that such a type of reinforcement is of no advantage in a column. Nevertheless, a closer inspection of these particular columns shows that the area of the protective shell occupied one-half of the entire cross-section of the column and had contact with the inside core over only one-fifth of its surface area. Furthermore, the bond between the flat surfaces of the column and the protective shell was not large. These considerations make it evident that the shell could not have taken its full share of the load. Accordingly, as soon as the maximum load on column B2 was reached, the pressure was immediately released, the apparatus removed and the protective shell knocked off. The apparatus was replaced on the core and the column re-tested. It stood a load of 246,000 pounds, or about eight-tenths of its former load. This showed conclusively that the protective shell did not carry its proportionate share of the maximum load in the previous tests. If the difference between the ultimate load of the column with the shell on and the maximum load sustained with it off is assumed to be carried by the protective shell, the unit stress sustained by the shell, allowing for thickness of lacing bars, etc., will be roughly 800 lbs/in^2, or only 40 per cent. of the average unit stress sustained by the total cross-section of the column.

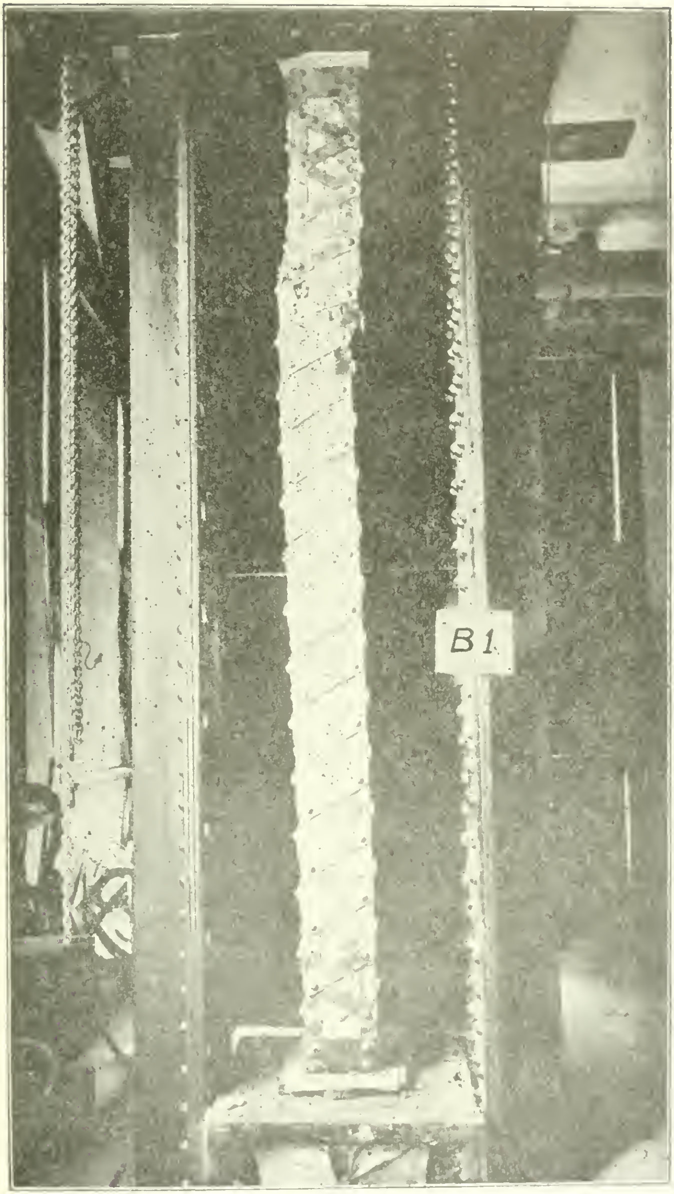

PLATE II. FAILURE OF COLUMN B1.

In order to study further the strength of the core in these columns, the protective shell was chipped off from columns B1 and B4 before they were tested. These columns had about the same ultimate strength as the core of column B2. Column B4 was somewhat weakened by a few small air pockets at the section where failure occurred. Plate II shows column B1 after failure.

In connection with series B, plain concrete column F1 and the steel column BS were tested. The results of these tests give information as to the strength of the concrete core without any reinforcement and the strength of the reinforcement without any concrete core. The column F1 sustained a maximum load of 120,600 pounds (or 1,880 lbs/in^2). The corresponding cylinders showed about the same ultimate strength as the cylinders B11 and B42, indicating that the concrete in F1 was of as good quality as the average found in the other columns of Series B. The stress deformation curve for this column is found in Fig. 10. The steel column BS had an elastic limit of 33,400 lbs/in^2, an ultimate strength of 48,000 lbs/in^2 and a modulus of elasticity of 26,000,000 lbs/in^2 (see stress-deformation curve, Fig. 6). The low value of the modulus may have been due to the rivets not entirely filling the rivet holes. The loads corresponding to the elastic limit and ultimate strength were 96,000 pounds and 138,000 pounds, respectively. Plate III shows column BS after failure.

From the tests of these last two columns and the cores of columns B1 and B4 it will be seen that the reinforced concrete cores held maximum loads nearly equal to the sum of the loads sustained by the plain concrete column F1 and the steel column BS. This clearly demonstrates that the steel and concrete act together in this type of column and may be counted upon in designing. The series also demonstrates that for this type of column the protective shell will remain intact until after the steel reaches its elastic limit. Also that while it may add some stiffness and strength to the column, it is an uncertain factor in this respect. For this reason it would not seem advisable to count on the strength or stiffness of the protective shell even though the danger of injury through fire be improbable.

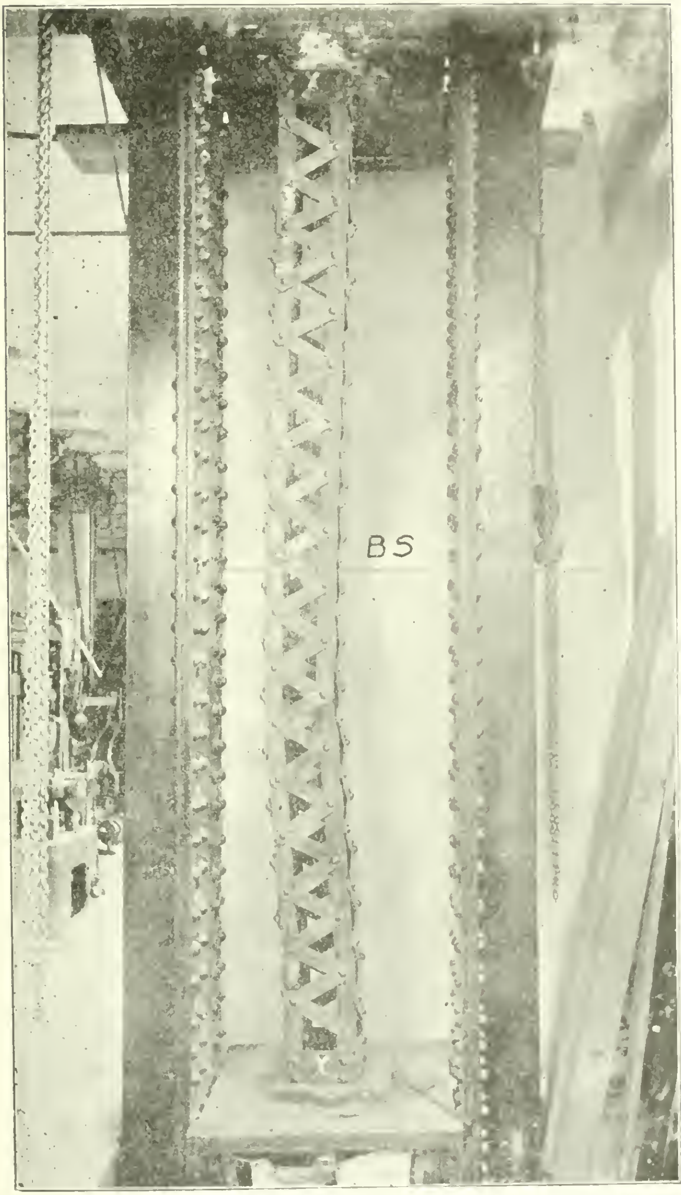

PLATE III.—FAILURE OF COLUMN BS.

Owing to the large area of the protective shell with respect to that of the inside core, the tests of B2 and B3 are not representative of this class of columns, but the high unit stresses sustained by the reinforced cores B1 and B4 (3,700 and 3,780 lbs in², respectively), even after they doubtless had been somewhat injured by removal of the outside shell, show that this method of reinforcing makes a strong column. Furthermore, if in steel construction, columns be fire proofed by concrete, these tests show that a large amount of additional strength can be obtained by filling the inside of the column with concrete.

The stress-deformation curves for columns B2 and B3 will be found in Fig. 6 and those for B1, B4 and B2 (re-tested) in Fig. 7. The curves for columns B2 and B3 are nearly identical. The same may also be said of the curves for the reinforced cores B1 and B4. In the latter the stress at which the steel reached its elastic limit is plainly shown by the sharp bends in the stress deformation curves.

4. SERIES C

The four columns of this series exhibited quite different properties from those of Series A or B. These columns were not only strong and held large compressive loads, but were also extremely tough. As the stress-deformation curves for this series indicate, (see Fig. 8) up to a certain point, although not as stiff, the columns of this series behaved much the same as plain concrete columns. But beyond this point the ratio of stress to deformation was much less, the curve becoming practically a straight line. This is well shown in the curves for C2 and C4. This point was also marked by the cracking of the protective shell. Owing to the failure of the protective shell, necessitating the removal of the apparatus, the curves for columns C1, C2 and C4 do not show the shortening at the maximum load. However, the last point on these curves does mark approximately the stress and deformation at which the shell completely failed.

It will be observed that the unit stresses used in plotting the stress-deformation curves in Fig. 8 are computed for the entire

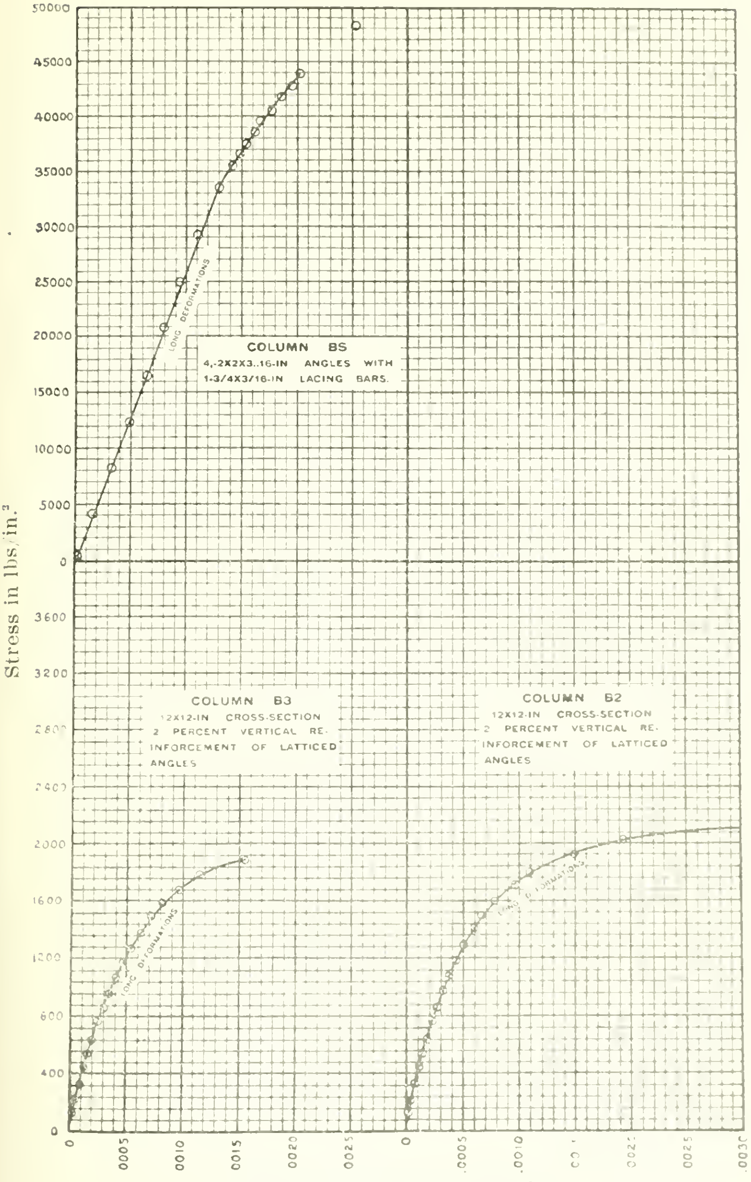

FIG. 6.—STRESS-DEFORMATION CURVES FOR COLUMNS B2, B3 AND BS.

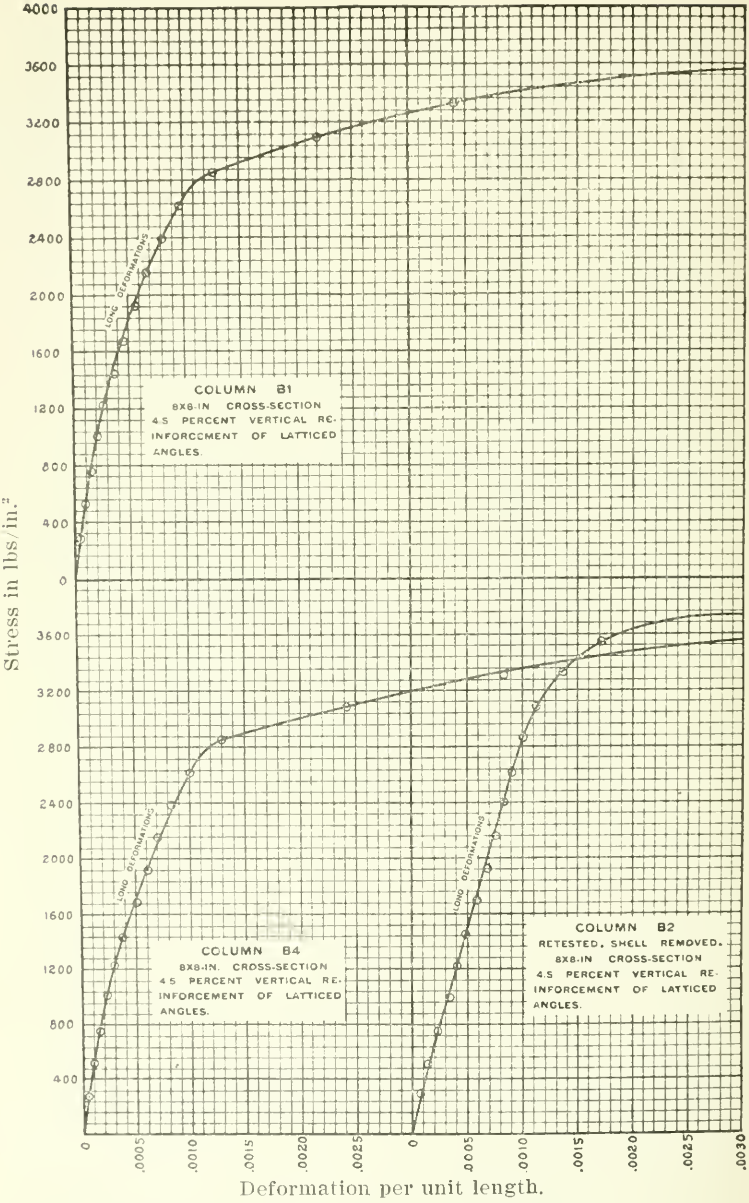

FIG. 7—STRESS-DEFORMATION CURVES FOR COLUMNS B1, B4 AND B2 RETESTED.

cross-section, but the ultimate strengths in Table VII are based upon the area inside of the spiral, as the protective shell had entirely fallen off at the maximum load.

After the maximum load was reached, the columns continued to shorten and deflect for some time while the load very slowly decreased. Column C4 deflected 4 in. before failing. Several of the columns gave good examples of restrained ends, a condition which was made evident both by the shape of the curve of the column and by the horizontal tension cracks appearing in the shell near the ends. Plates IV and V give views of columns C2 and C3 at failure.

Column C1 failed by deflecting laterally so far out of line that one of the spacing straps snapped in tension. A piece of the spiral taken from the vicinity of the break appeared to have sealed and when tested showed a yield point 30 per cent. higher than a piece taken from the end of the column. This was the only example of a spiral being over-stressed which was noted in testing either Series C or D.

As has been said before, some difficulty was encountered in keeping the spirals straight and in the center of the forms while the columns were being made, owing to their lack of rigidity. When column C3 was stripped of its protective shell before testing, the spiral was found to be bent at one place nearly an inch out of line. After the shell came off of column C4, the spiral was found to be out of center of the column about one-half an inch. On account of these defects in fabrication, these two columns did not stand as high loads as their mates, columns C1 and C2.

Column C3 was stripped of its shell before testing in order that the strength and elastic properties of the core alone might be studied. It will be observed that the stress-deformation curve is practically the same as the average curve for columns C1, C2 and C4, as shown in Fig. 11, up to a stress of 1,600 lbs/in². It was also at approximately the deformation corresponding to this stress that the protective shell on these columns cracked. This indicates that the shell and core in columns C1, C2 and C4 acted in unison up to this stress.

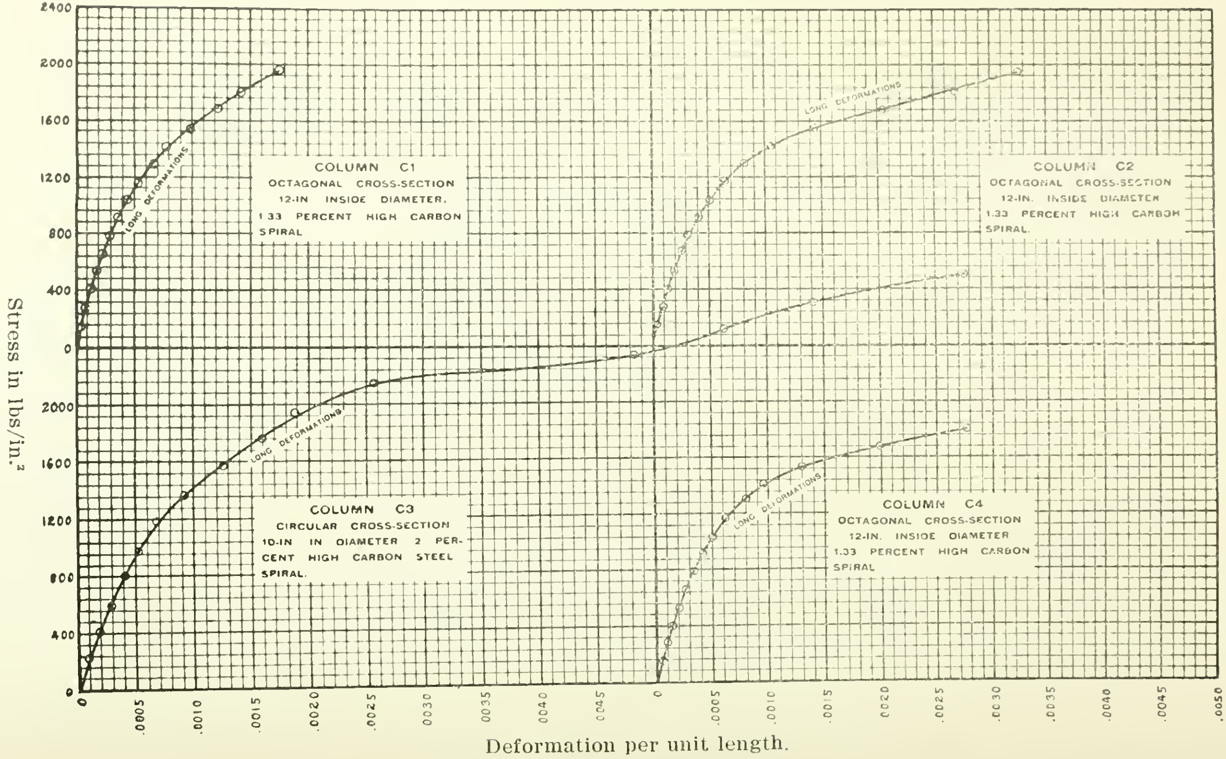

Fig. 8.—Stress-Deformation Curves for Columns of Series C.

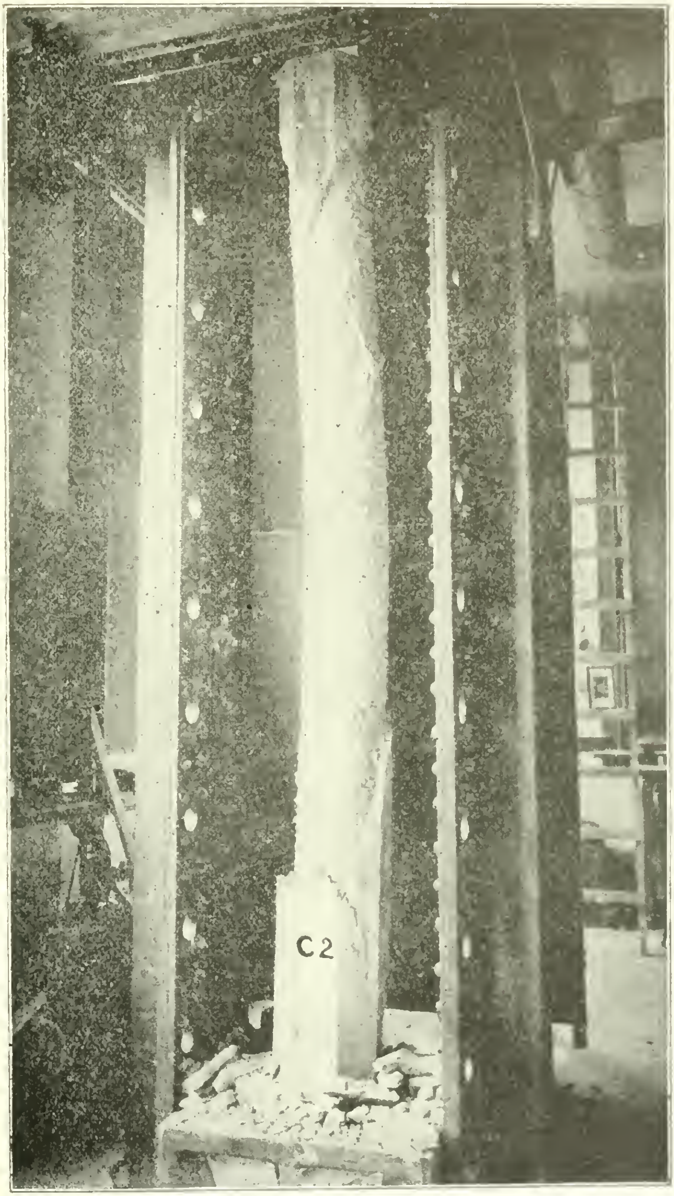

Plate IV.—Failure of Column C2.

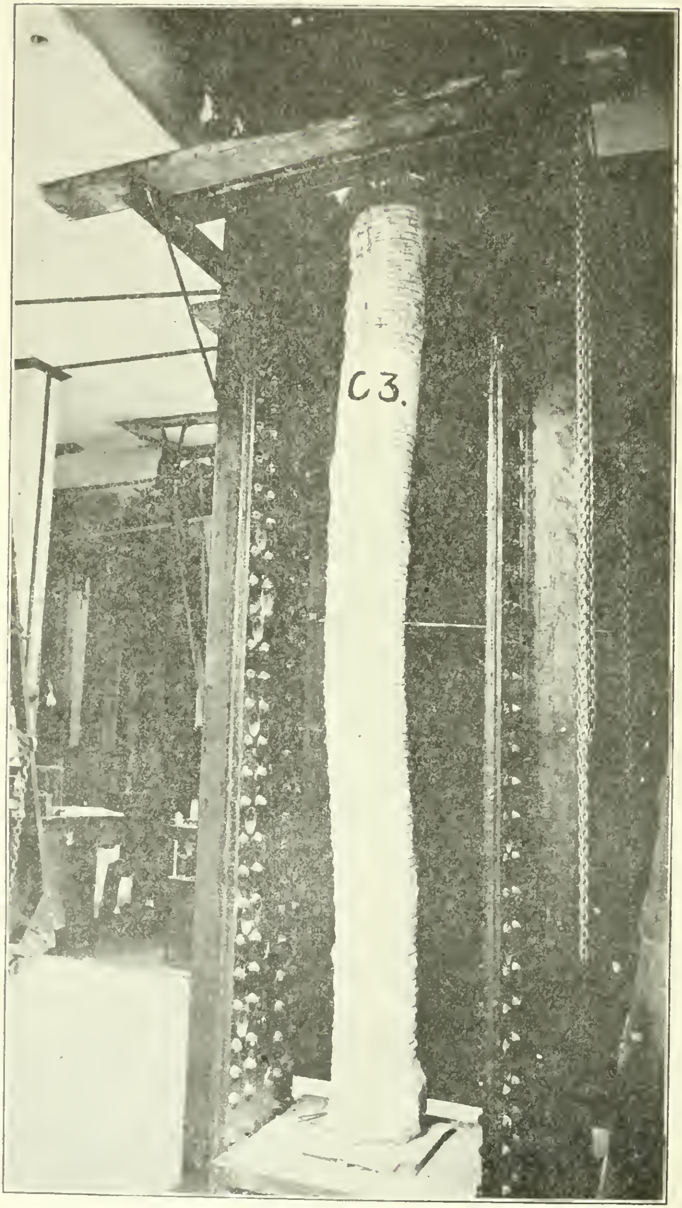

Plate V.—Failure of Column C3.

In considering the increase in ultimate strength over that of the plain concrete columns per per cent. of spiral, the percentages for columns C1, C2 and C4 should be based on the core area. Using this value of two per cent. and the ultimate strength given in Table VII, the increase in ultimate strength for one per cent. spiral over the average ultimate strength of the columns of Series A is 1,295, 1,160, 795 and 670 lbs/in^2 for columns C1, C2, C3 and C4, respectively, or an average increase for Series C of 980 lbs/in^2.

5. Series D

These columns, while retaining the toughness of those of Series C showed a marked increase in stiffness and a considerably higher ultimate strength. The unit stress at which the protective shell began to disintegrate was considerably higher than in Series C. As in Series B the deformation at which this shell began to crack indicates that the steel had been stressed beyond its elastic limit. Complete failure of the protective shell occurred at stresses and deformations slightly greater than the last points plotted on the stress-deformation curves, Fig. 9, would indicate.

As in Series C it will be noted that the unit stresses for these curves are based upon the total cross-sectional area of the column. Values of the ultimate strength given in Table VII are figured for the core area inside the spiral as the strength of protective shell was entirely destroyed before the maximum load was reached.

Columns D1 and D2 were progressively loaded to failure. Column D3 was subjected to two repetitions of 1,040 lbs/in^2 (based on total area) and then progressively loaded to failure. In making these repetitive loadings dial readings corresponding to zero loads were taken about two minutes after the pressure was released. The load was then immediately re-applied. The sets per unit of length after the first and second repetitions were .000035 and .000037, respectively. This column bent $2\frac{1}{2}$ inches out of line at the maximum load, 391,000 pounds. Then

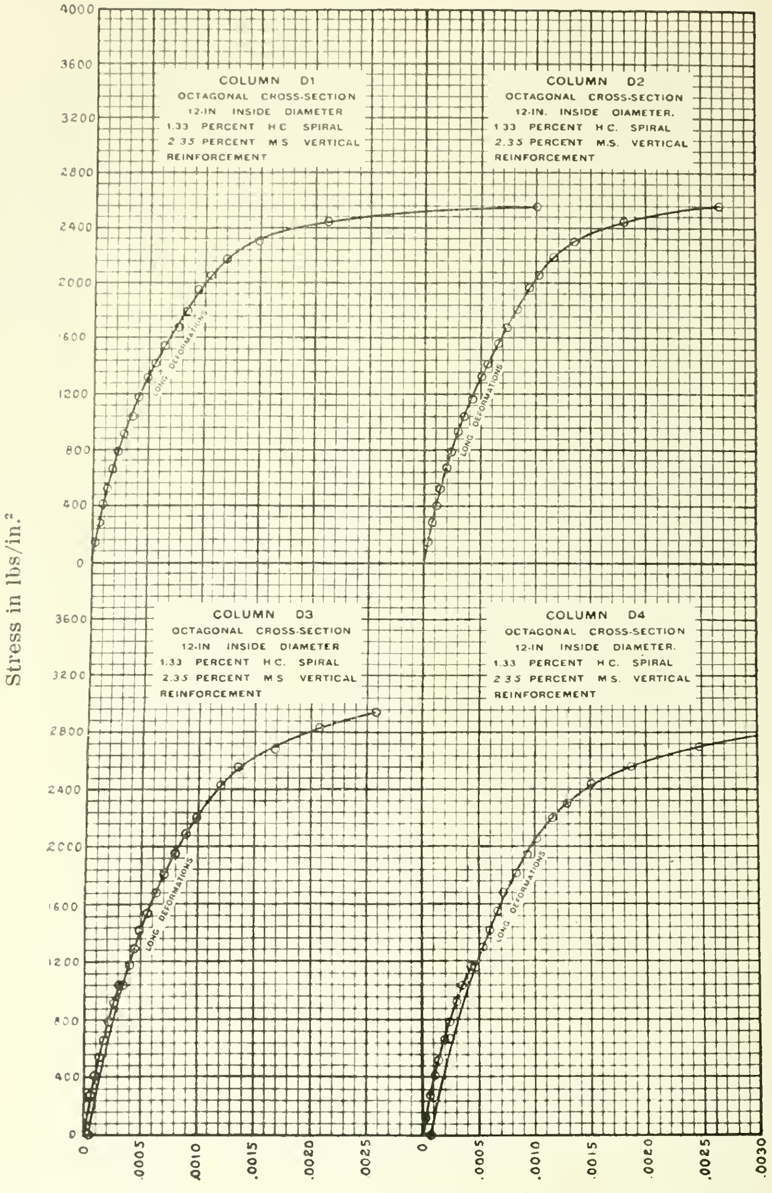

FIG. 9.—STRESS-DEFORMATION CURVES FOR COLUMNS OF SERIES D.

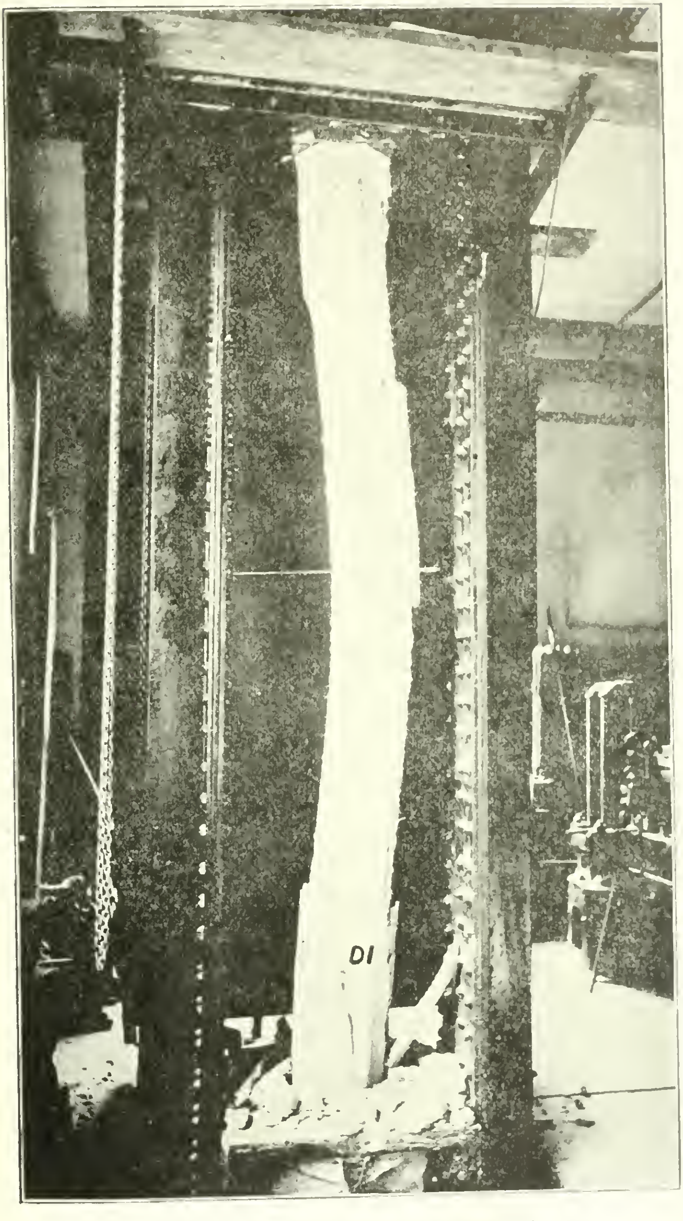

Plate VI.—Failure of Column D1.

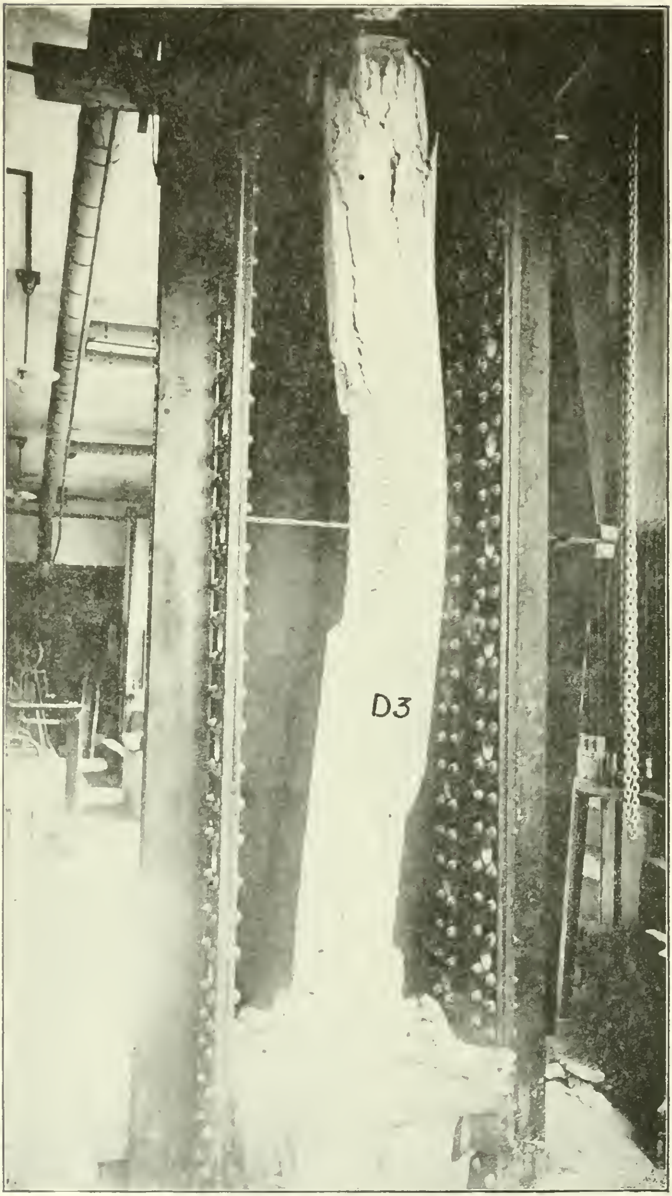

Plate VII.—Failure of Column D3.

the load slowly fell off. At a load of 333,000 pounds the shortening of the column was found to be about 2 inches.

Column D4 was given three repetitions of 1,170 lbs/in² and then progressively loaded to failure. The sets per unit of length for the first, second and third repetitions were, respectively, .000060, .000066 and .000080. On the second application of the load the stress-deformation curve became a straight line up to the repetition limit. The interval between repetitions was two minutes, except for the third repetition, which was made after a rest of an hour and a half.

Plates VI and VII are views of columns D1 and D3, taken after the maximum load had been applied. They are characteristic for this type of column, showing the disintegration of the outside shell and the large deflection of the core.

It is of interest, in comparing Series C and D, to compute the increase in ultimate strength in Series D over that in Series C for one per cent. of longitudinal reinforcement. For such a comparison the percentage of vertical steel should be figured for the area of the core. On this basis the per cent. of longitudinal steel for Series D is 3.53. The average ultimate strengths for Seriese C and D are 4,030 and 4,750 lbs/in², respectiveley. Therefore the average increase in ultimate strength of Series D above that of Series C for one per cent. longitudinal reinforcement is about 204 lbs/in². A similar computation may be made noting the increase in strength for per cent. of vertical reinforcement for Series D at the point where the protective shell began to disintegrate. The average unit stress on the whole area at this point was 1,712 lbs/in² for Series C and 2,373 lbs/in² for Series D. Then for the point at which the protecting shell failed, the increase per per cent. of longitudinal reinforcement is 661 : 2.35 or 282 lbs/in².

6. Series E

When tested, the columns of this series, although somewhat stiffer, showed similar characteristics to those exhibited by the columns of Series D, until the deformations indicated that the yield point of the steel had been reached. At this point, however, owing to the insufficient lateral support offered by the

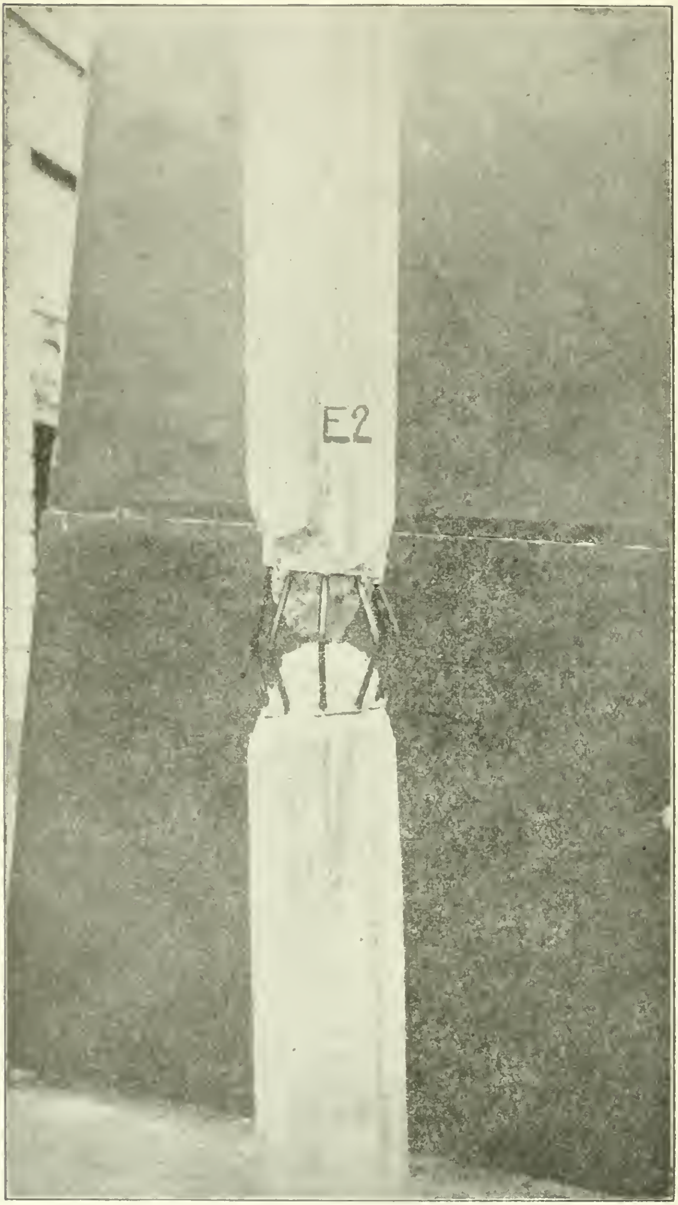

PLATE VIII.—FAILURE OF COLUMN E2.

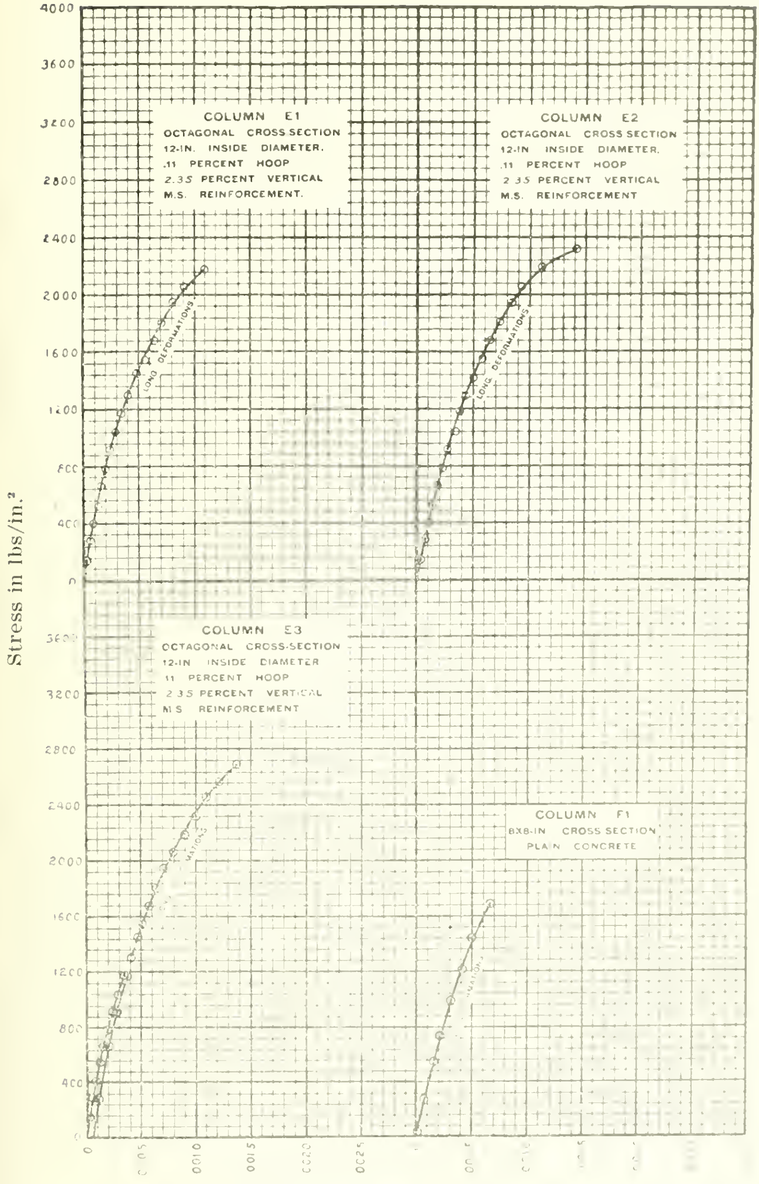

FIG. 10.—STRESS-DEFORMATION CURVES FOR COLUMNS E1, E2, E3 AND F1

widely separated bands, they failed very suddenly. Plate VIII shows the failure of column E2, which was characteristic of the others tested. The concrete failed in the same way as it did in some of the plain columns. The reinforcement, of course, buckled between the ¼-inch ties.

Column E3 was subjected to three repetitions of 1,170 lbs/in², the interval between release and re-application of load being about one and one-half minutes. The sets per unit of length after the first, second and third repetitions were .000045, 000057 and .000061, respectively. The column was then progressively loaded to failure.

The stress-deformation curves for this series will be found in Fig. 10. These curves for E2 and E3 were completely obtained. The apparatus was removed from E1 before the maximum load was reached.

The increase in ultimate strength per per cent. of longitudinal reinforcement for columns of this series over the ultimate strength of the plain columns of Series A is approximately 156 lbs/in².

7. COMPARISON OF TYPES OF REINFORCED COLUMNS TESTED

TABLE VIII.

VALUES OBTAINED FROM TESTS OF REINFORCED COLUMNS. LOADS, STRESSES, AND DEFORMATIONS AT WHICH THE PROTECTIVE SHELL OF CONCRETE CRACKED.

COL. NO.	KIND OF REINFORCEMENT.	At Cracking of Protective Shell.			
		Loads lbs. P_1	Unit stress lbs/in²*	Unit deformation.	Ratio $\frac{P_1}{P}$
B1	4, 2 x 2 x $\frac{3}{16}$-in. latticed angles.	†183,000	2,860	.0013	.77
B4		†183,000	2,860	.0013	.76
B2		273,000	1,920	.0015	.90
B3		280,000	1,960	.0015	.97
C1	¼—in. high carbon steel spiral, 10-in. diam. 1-in. pitch.	213,000	1,800	.0014	.58
C2		183,000	1,550	.0014	.53
C3		‡153,000	1,950	.0019	.53
C4		183,000	1,550	.0013	.68
D1	9, ⅝-in. round mild steel rods and ¼-in. high carbon steel spiral. 10- in. diam. 1-in. pitch.	258,000	2,180	.0012	.74
D2		273,000	2,310	.0013	.83
D3		303,000	2,560	.0014	.77
D4		288,000	2,440	.0015	.68
E1	9, ⅝-in. round mild steel rods, ¼-in ties 1 ft. c. to c.	273,000	2,310	....	1.00
E2		273,000	2,310	.0014	1.00
E3		318,000	2,695	.0014	1.00

* Unit stresses for all series $=\frac{P_1}{\text{Total area.}}$

† Angles sealed.

‡ Spacing straps buckling.

In order to form a comparison of these different types of columns some results obtained from the tests have been tabulated in Tables VIII, IX, and X. Fig. 11 contains average stress-deformation curves for the different types of columns tested. In Table VIII are recorded the loads (P_1) and the stresses at which there were plainly discernable in the protective shell cracks of such size as to indicate it in unsafe condition for fire proofing purposes. The unit deformations given in the fourth column show that the longitudinal metal had reached its elastic limit in every case. The crosses in Fig. 11 indicate the point at which the protective shell cracked. The ratio P_1/P gives the proportion of the ultimate load carried before this protective shell cracked. It is the inverse of the factor of safety for this load and is also in these tests indicative of the relative toughness of the column.

TABLE IX.

VALUES COMPUTED FROM COLUMN TESTS.

Stresses in Concrete and Steel and Values of n for Deformation per Unit of Length of .0004.

COL. No.	REINFORCEMENT.		Load lbs. P_2	Unit stress on entire cross-section lbs/in².	Unit stress on concrete lbs in² f_c.	Unit stress on vertical steel lbs in² f_s.	n $\frac{E_s}{E_c}$ $\frac{f_s}{f_c}$.
	Per cent. vertical.	Per cent. lateral.					
B1	4.5	....	100,000	1.560	1.145	10.400	9.1
B4	4.5	....	96,000	1,500	1.080	10.400	9.6
B2	2.0	....	160,000	1,120	930	10.400	11.2
B3	2.0	....	150,000	1,050	860	10.400	12.1
C1	....	1.33	117,000	990	990	....	....
C2	....	1.33	106,000	900	900	....	....
C3	....	2.00	64,000	810	810	....	....
C4	....	1.33	109,000	920	920	....	....
D1	2.35	1.33	136,000	1,150	890	12,000	13.5
D2	2.35	1.33	135,000	1,140	880	12,000	13.6
D3	2.35	1.33	146,000	1,240	980	12,000	12.2
D4	2.35	1.33	135,000	1,140	880	12,000	13.6
E1	2.35	0.11	150,000	1,270	1,010	12,000	11.9
E2	2.35	0.11	145,000	1,230	970	12,000	12.1
E3	2.35	0.11	151,000	1,280	1,020	12,000	11.8

Table IX contains the values of the stresses in the concrete and steel for a unit deformation (selected simply for purposes

SERIES A—12x12-in. sq. cross-section; plain concrete; av. ult. stress = 2,070 lbs. per sq. in.

SERIES B—B1&B4, core only, 8x8-in. sq. section 4.5 percent vertical reinforcement; B2&B3 12x12-in. sq. cross-section 2 percent vertical reinforcement; 4, 2x2x3/16-in. latticed angles in all columns; av. ult. stress B1&4 = 3,740 lbs. per sq. in., B2&3 = 2,070 lbs. per sq. in.

SERIES C—C1,C2,&C4 octagonal section 12-in. inside diam. 1.33 percent spiral reinforcement; C3 circular section 10 in. in diam. 2 percent spiral reinforcement; ¼-in. high carbon steel spiral 10 in. diam. 1-in. pitch; av. ult. stress C1,C2,&C3 = 4,150 lbs. per sq. in., C3 = 3,660 lbs. per sq. in.

SERIES D—Octagonal section 12-in. inside diam. 1.33 percent spiral & 2.35 percent vertical reinforcement; spirals the same as in series C; 9,-5/8-in. mild steel rods: av. ult. stress = 4,750 lbs. per sq. in.

SERIES E—Octagonal section 12-in. inside diam. .11 percent hoop & 2.35 percent vertical reinforcement; ¼-in. mild steel hoops 10-in. in diam. 1-ft. c. to c; same vertical reinforcement as in series D; av. ult. stress = 2,410 lbs. per sq. in.

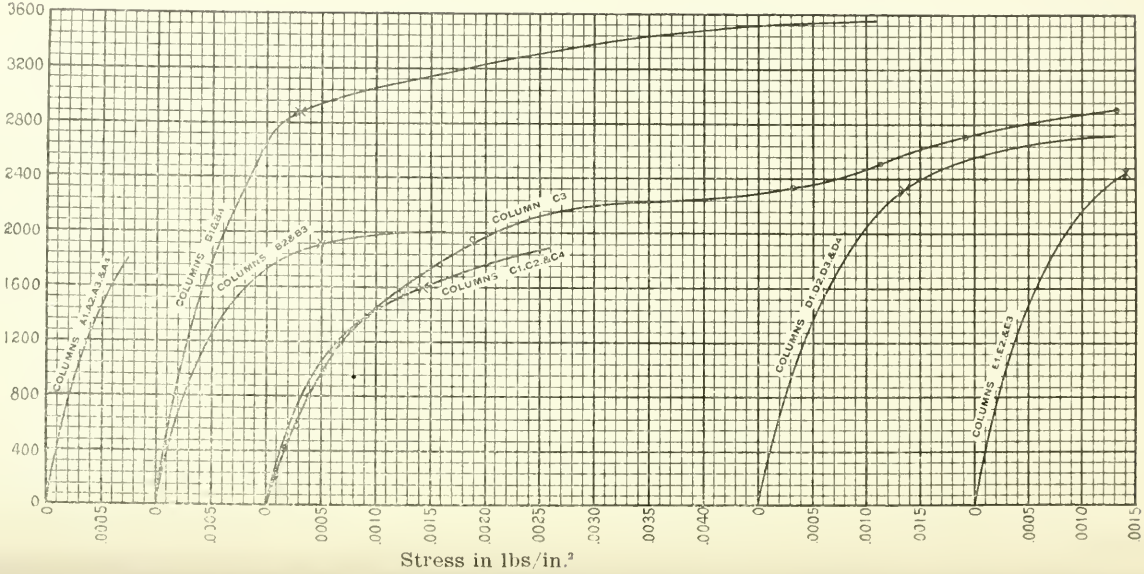

FIG. 11.—STRESS IN POUNDS PER SQUARE INCH (BASED ON GROSS CROSS-SECTION).

of comparison) of .0004. These were obtained from the following equations:

$$f_s = E_s \varepsilon$$

$$f_c = \frac{P - A_s f_s}{A - A_s}$$

In these equations f_s and f_c are the unit stresses in the steel and concrete, respectively, produced at a unit deformation $\epsilon = .0004$; E_s is the modulus of elasticity of steel; $P = P_2$ is the load corresponding to ϵ; A is the total area of the column; A_s is the area of the steel. The modulus of elasticity was assumed as 30,000,000 lbs/in² for the steel in Series D and E. For Series B the value 26,000,000 lbs/in² taken from the test of column BS was used.

TABLE X.

Factors of Safety of Columns Tested Computed With Reference to Maximum Loads and Loads at Which the Protective Shell Cracked.

Load (P_3) is Computed by Assuming Unit Stresses Found in Table IX to Act on Core Alone.

Col. No.	Core area, sq. in. C	Maximum load lbs. P	Load at failure of shell, lbs. P_1	Unit stresses at unit deformation .0004. Concrete lbs/in² f_c	St lbs/in² f_s	Coreload $f_c(C-A_s) + A_s f_s$ lbs P_3	$\frac{P}{P_3}$	$\frac{P_1}{P_3}$
*B1	64	237,000	183,000	1,145	10,400	100,000	2.4	1.8
*B4	64	242,000	183,000	1,080	10,400	96,000	2.5	1.9
B2	64	303,000	273,000	930	10,400	87,000	3.5	3.1
B3	64	288,000	280,000	850	10,400	83,000	3.5	3.4
C1	78.5	366,000	213,000	990	....	78,000	4.7	2.7
C2	78.5	345,000	183,000	900	....	71,000	4.9	2.6
*C3	78.5	288,000	153,000	810	....	64,000	4.5	2.4
C4	78.5	268,000	183,000	920	....	72,000	3.7	2.5
D1	78.5	351,000	258,000	890	12,000	101,000	3.5	2.6
D2	78.5	330,000	273,000	880	12,000	100,000	3.3	2.7
D3	78.5	391,000	303,000	980	12,000	108,000	3.6	2.8
D4	78.5	421,000	288,000	880	12,000	100,000	4.2	2.9
E1	78.5	273,000	273,000	1,010	12,000	110,000	2.5	2.5
E2	78.5	273,000	273,000	970	12,000	107,000	2.6	2.6
E3	78.5	318,000	318,000	1,020	12,000	110,000	2.9	2.9

* Protective shell removed before testing.

Values from Tables VII, VIII, and IX were used in making up Table X. From the unit stresses obtained in Table IX the load which could be carried by the core alone (P_3) was calculated and is found in column No. 7. The factors of safety f, based upon maximum loads, and f_1, based upon loads at which the protective shell cracked, are of assistance in making a comparison of the strengths of the types of reinforced columns tested. This fact must also be borne in mind in comparing these different columns that the maximum load for Series E was partially sustained by the protective shell, while in Series C and D and in columns B1 and B4 it was sustained by the core alone. If the protective shell of such columns as those of Series E was seriously injured by fire the ultimate strength would be impaired as replastering would not replace the strength lost by the injury. In columns of the type of Series D, however, injury to the protective shell would not decrease the maximum load carrying capacity.

V. SUMMARY

1. The 1:2:4 plain concrete columns of Series A had an average modulus of elasticity of 3,850,000 lbs/in², an ultimate strength of 2,070 lbs/in². Although these columns were of exceptionally uniform strength, under practical working conditions the liability of variations in strength and eccentricity of loading make the use of low working stresses imperative for such a brittle material. Consequently it is often desirable to employ a reinforcement which will make the use of higher working stresses possible.

2. The tests of the cores of columns of Series B, reinforced with 4.5 per cent. of longitudinal steel (latticed angle columns) gave an average modulus of elasticity of 4,100,000 lbs/in² and an average ultimate strength of 3,740 lbs/in². These cores exhibited considerable toughness before failure. The plain concrete column F1 of the same cross-sectional area had a modulus of elasticity of 3,800,000 lbs/in² and an ultimate strength of 1,880 lbs/in². Comparing the strength of the cores with that of the steel column BS indicates a means of increasing the strength of the hollow steel section by filling the inside with concrete.

In the tests of columns B2 and B3 the area of the outside shell was so large in proportion to the area of the core that the value of the form of reinforcement was obscured. The tests of these two columns in connection with columns B1 and B4 indicate that the protective shell cannot be relied upon to carry load in this type of column, especially when there is relatively little direct bond between it and the concrete core. They also show, however, that the shell remained intact until the yield point of the steel was passed.

3. The columns 1.33 per cent. spiral reinforcement, Series C, had an average modulus of elasticity of 2,200,000 lbs/in², an

average ultimate strength of 4,030 lbs/in^2 and were exceptionally tough. The protective shell began to disintegrate at about six-tenths of the maximum load. These columns were not stiff enough to carry high working loads. (Compare column 7 Table X for Series C and D.)

4. The columns with 1.33 per cent. spiral and 2.35 per cent. longitudinal reinforcement had an average modulus of elasticity of about 3,100,000 lbs/in^2 and an average ultimate strength of 4,750 lbs/in^2. They were also extremely tough. They sustained three-fourths of their maximum load before the protective shell began to disintegrate. As shown in Table X, on the core area, they were capable of carrying the high stresses of 900 and 1,200 lbs/in^2 on the concrete and longitudinal steel respectively with a factor of safety based on the ultimate strength of 3.6 or 2.7 based on the load at which the protective shell cracked.

Of the columns tested this series exhibited structural qualities of the highest grade. The longitudinal reinforcement furnished the requisite stiffness for high working loads, while the spiral provided a high ultimate strength and great toughness necessary as a factor of safety.

5. The columns reinforced with longitudinal rods and ties 1 foot apart had a modulus of elasticity averaging about 3,800,000 lbs/in^2 and an ultimate strength of 2,440 lbs/in^2. They failed suddenly and completely at longitudinal deformations corresponding to the yield point in the steel, the vertical rods bulging out between the widely spaced ties. These columns could not carry with safety as high working stresses as the columns of Series B or D.

A further investigation of the strength and elastic properties of concrete columns reinforced with different percentages of spiral and longitudinal reinforcement is now in progress.

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INVESTIGATION OF CENTRIFUGAL PUMPS

PART II

EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP, COMPARING THE EFFICIENCY OF CIRCULAR AND SPIRAL CASES AND SHOWING THE EFFECT OF AIR LEAKAGE

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INVESTIGATION OF CENTRIFUGAL PUMPS—II

INTRODUCTION

Part I of the "Investigation of Centrifugal Pumps," gave the results of experiments with a six-inch vertical centrifugal pump, comparing the efficiency of various forms of impellers of the enclosed radial type; also a discussion of the theory of the centrifugal pump and an index of literature on the subject of centrifugal pumps, between 1850 and 1907.

The present bulletin, Part II of the investigation, gives results of experiments with a six inch horizontal centrifugal pump. The pump was designed especially for experimental purposes, and was so arranged that various forms of impellers and pump cases could readily be used with it. The same impellers used in the six inch vertical centrifugal pump, could be used with the six-inch horizontal centrifugal pump, so the results submitted in Part I of the investigation could be verified, and also further extended to cover results with vanes curved forward and backward. Before extending the study of the influence of the shape of the vanes on efficiency and capacity of the pump, it was considered best to make a brief study of the effect of the form of the casing. Part II, following, is the result of this study, and gives results of experiments comparing the efficiency of circular and spiral cases, and showing the effect of air leakage. The experiments were made in the Hydraulic Laboratory of the University of Wisconsin between February, 1906, and April, 1908.

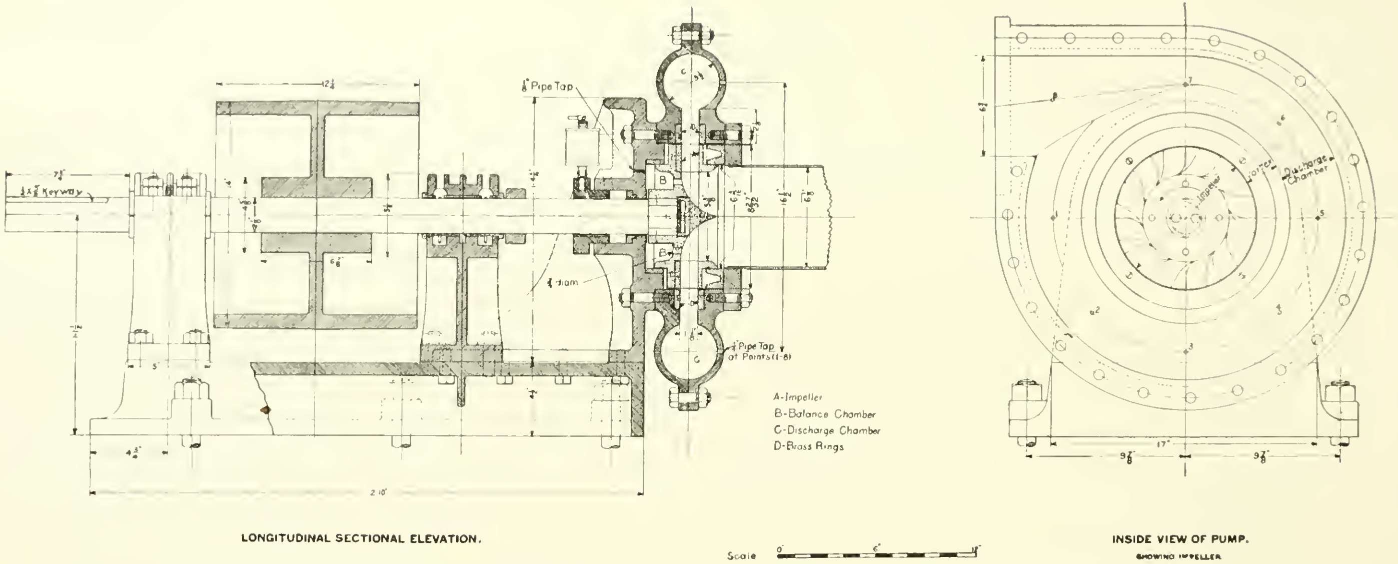
Credit for the design of the six inch horizontal centrifugal pump, and for the inception and general plan of the investigation is due to Daniel W. Mead, Professor of Hydraulic and Sanitary Engineering at the University of Wisconsin. The pump was constructed in the mechanician's shop of the University of Wisconsin, under the direction of Mr. E. H. J. Lorenz, to whom credit is due for careful workmanship. In the portion of the investigation, "Experiments with spiral casing," the writer was assisted by Mr. E. Olson, who has submitted a portion of the data, in slightly different form, for the degree of B. S. in E. E. at the University of Wisconsin. The writer also desires to acknowledge the services of Mr. J. R. Sherman and Mr. W. A. Gattiker, who have assisted in the general arrangement of the drawings and the tabular matter.

DESCRIPTION OF SIX INCH HORIZONTAL CENTRIFUGAL PUMP

The pump shown in detail, Plate I, was designed as an experimental pump, and so arranged that various forms of impellers and pump cases could readily be used with it. The impellers were of the enclosed type, eight and thirteen-sixteenth inches outside diameter, with radial vanes, and are shown in Plates VI and VII of Part I of the "Investigation of Centrifugal Pumps." Throughout the experiments described in this bulletin, the impeller used remained the same and, as may be seen, Plate I, was of the enclosed type with 12 radial vanes, having the entrance modified by a suitable curve, to assure gradual change of direction of the water and entrance without shock. The outer portion of the metal of each vane had such a thickness that the area of cross-section of the waterways through the impeller remained practically constant from inlet to outlet. The impeller was attached, by counter sunk screws, to a brass casting which was keyed to the pump shaft, as shown in Plate I. All surfaces of impeller and brass casting were smooth.

In addition to the possibility of using impellers of various forms, the pump casing could also be easily removed and one of another form substituted. Plate II shows the details of the circular and spiral cases used in the experiments described in this bulletin. In the circular case, the discharge chamber, which collects the water and leads it to the six inch discharge pipe, was circular in form and had a circular cross-section, the diameter being three and one-half inches. The connection to the six inch discharge pipe was made by gradually enlarging the cross-section, thus forming a diverging tube having a length as shown of about thirteen inches.

In the spiral case, the discharge chamber, as shown, was approximately a spiral in form, the outer edge of the chamber being a four center curve, and having a pitch of six inches in three hundred and sixty degrees. The discharge chamber was circular in cross-section, except near the beginning or throat, and had a gradually increasing diameter.



LONGITUDINAL SECTIONAL ELEVATION.

INSIDE VIEW OF PUMP.
SHOWING IMPELLER

PLATE I—EXPERIMENTS WITH A 6-INCH HORIZONTAL CENTRIFUGAL PUMP.

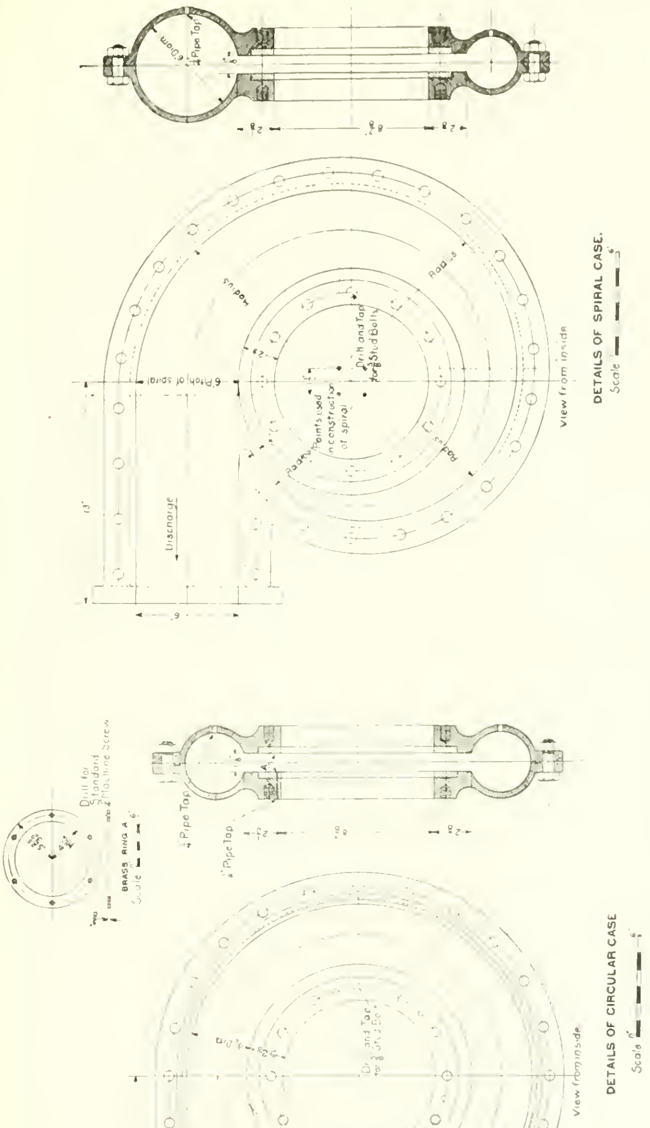


PLATE II—EXPERIMENTS WITH A 6-INCH HORIZONTAL CENTRIFUGAL PUMP.

Details of Circular Case and Spiral Case.

The beginning of the discharge or collecting chamber, termed the throat, was thus nearly closed in the spiral case, the dimensions at this point being approximately one and one-eighth inches by one-half inch; while in the circular case the throat was open, circular in cross-section, and had a diameter of three and one-half inches.

The annular space extending from the periphery of the impeller to the entrance to the discharge or collecting chamber, has been termed the vortex chamber. In both the circular and spiral cases experimented with, the form of the vortex chamber remained the same, being rectangular in cross-section, one and one-eighth inches wide and two and one-eighth inches long. In future experiments it is planned to modify the form of the vortex chamber, as for example, to increase the outer width and make a diverging entrance to the discharge chamber, and thus eliminate eddies which may result from the shoulder at this point.

A balance chamber, B, was arranged on the rear side of the impeller, as shown, and connected to the suction side of the impeller by four holes, each hole being three-quarters of an inch in diameter. The pump shaft was supported by brass lined bearings having ring oilers.

ARRANGEMENT OF PUMP AND APPARATUS FOR EXPERIMENTS

General Arrangement of Pump

For the first experiments with the six inch horizontal centrifugal pump, the entrance to the pump was arranged to be under suction as shown on Plate III. In this arrangement considerable trouble was experienced from leakage of air into the pump through the stuffing box, and it was found necessary to put the entrance to the pump under pressure as shown on Plate IV. In the rearranging and placing of the entrance to the pump under pressure, as shown, the 25 H. P. electrical motor, used with the first experiments, was replaced by a 50 H. P. electrical motor.

Weir for Measurement of Water

The water pumped was measured by the flow over an eighteen inch sharp crested weir with end contractions, the water returning to the suction pit to be repumped. The weir and weir box used were the same as used in previous experiments and are described in the bulletin "Investigations of Centrifugal Pumps, Part I," page 479.

Piezometers

In order to determine the most suitable form of piezometer, for measuring the discharge and suction heads of the pump, an experimental investigation was made of various forms of piezometers. The general form adopted is shown by Plate V. It was made of cast iron and inserted between the standard flange joints of the six inch discharge and suction pipes. In the various forms of piezometers which were compared, the width of the annular opening, through the brass lining into the six inch pipe, was varied, being $\frac{1}{64}$ inch, $\frac{1}{32}$ inch, and $\frac{1}{16}$ inch respectively. Comparisons were also made between these piezometers with annular openings and one having four holes through the brass lining, each hole having a diameter of $\frac{3}{32}$ inches, and

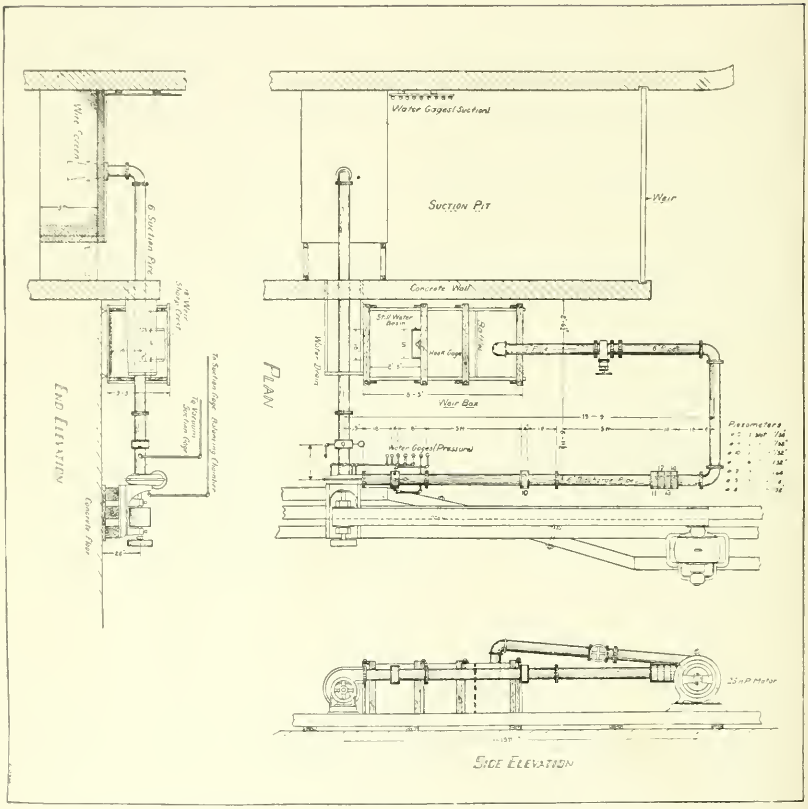


Plate III—Experiments with a 6-inch Horizontal Centrifugal Pump. General Arrangement, Entrance to Pump under Suction.

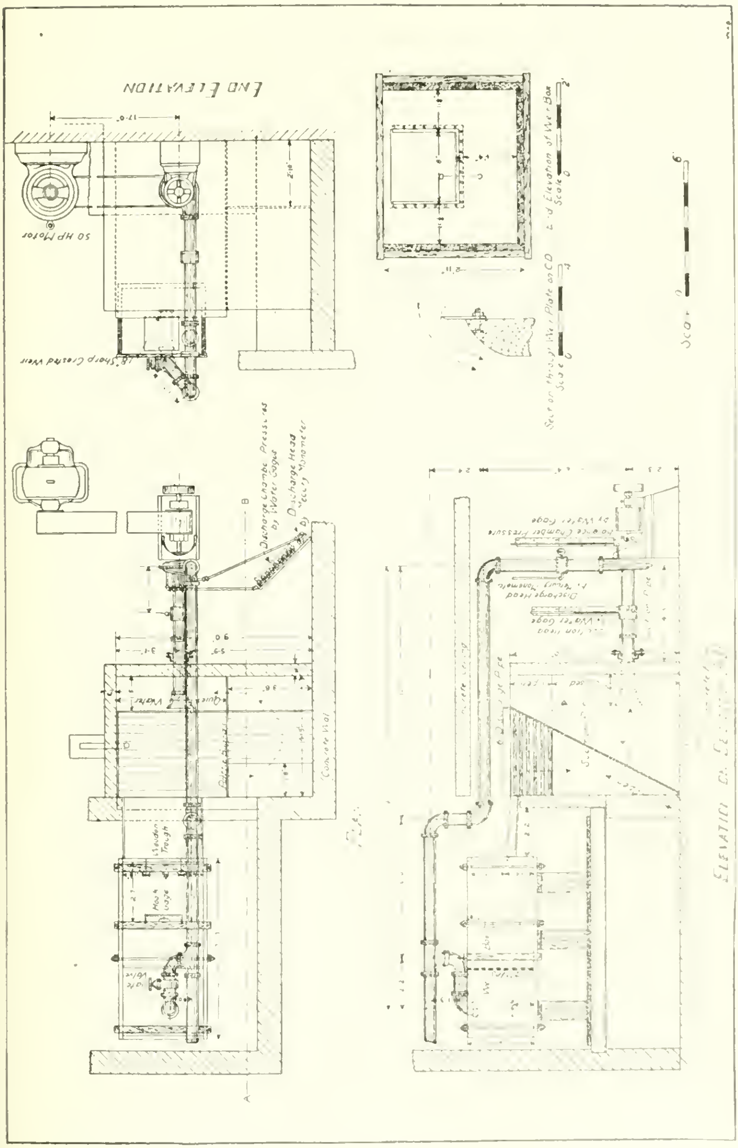


PLATE IV.—EXPERIMENTS WITH A 6-INCH HORIZONTAL CENTRIFUGAL PUMP.
General Arrangement, Entrance to Pump under Pressure.

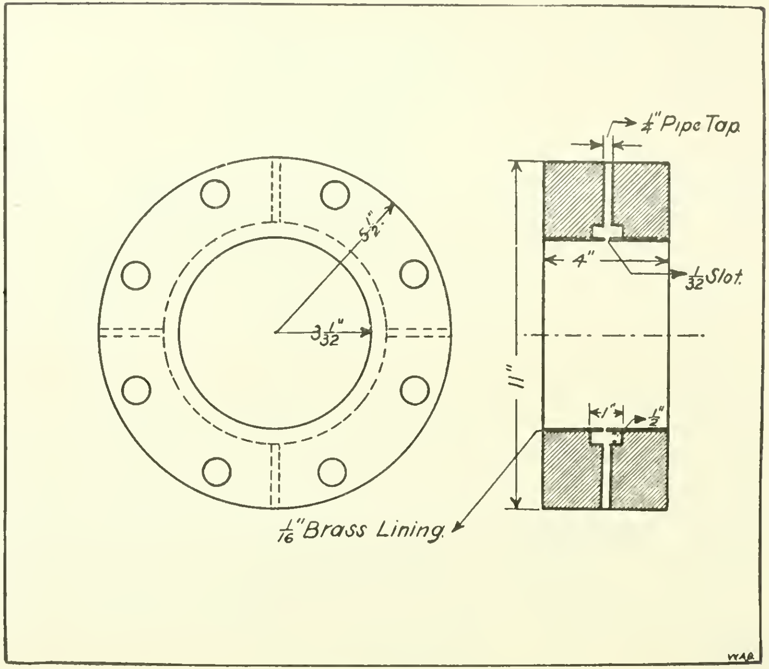


PLATE V—DETAILS OF PIEZOMETER.

located at quarter points of the circumference, and likewise between the piezometers with annular openings and the ordinary form of piezometer connection, made by inserting a $\frac{1}{4}$ inch iron pipe, flush with the inside surface of the six inch pipe. Plate III shows the general arrangement of the six inch discharge pipe for making the comparison. The piezometers were arranged adjoining each other and careful measurements made of the variations in pressure between piezometers by means of a differential oil gage, proper allowance being made for loss of head in the six inch brass pipe between centers of piezometers. The results of the investigation showed a small but measurable difference between the various forms, but for the purpose in view, it was found amply accurate to use any of the various forms with annular openings, and the form having such opening $\frac{1}{32}$ inch wide was adopted as standard. It is planned to publish the results of the investigation, and description of the methods used, as a separate University bulletin.

The piezometers for measuring discharge head and suction head were placed, as shown on Plate III and Plate IV, one and one-half feet from the outlet and inlet of the pump respectively.

MERCURY MANOMETERS AND WATER GAGES

It was desired to measure the pressure and velocity at various points of the pump casing, and in order to do so conveniently a rather complicated system of gages was necessary. It was found that the pressures in various portions of the vortex were less than atmospheric and these required suction gages. Ordinary pressure and vacuum gages of the Bourdon type could not be depended on for values much closer than about one foot and were discarded, except for use as a check in certain cases of measurement of discharge head and suction head. Plate VI is a photograph showing the pump with connections to water gages and mercury manometer for measuring pressures. Plate VII is a diagrammatic sketch showing the general arrangement of the pressure and suction gages. Referring to the discharge chamber, Plate VII, it will be observed that the points, Nos. 1–8, located on the center line of the discharge chamber, are connected by rubber tubing, to the water gages

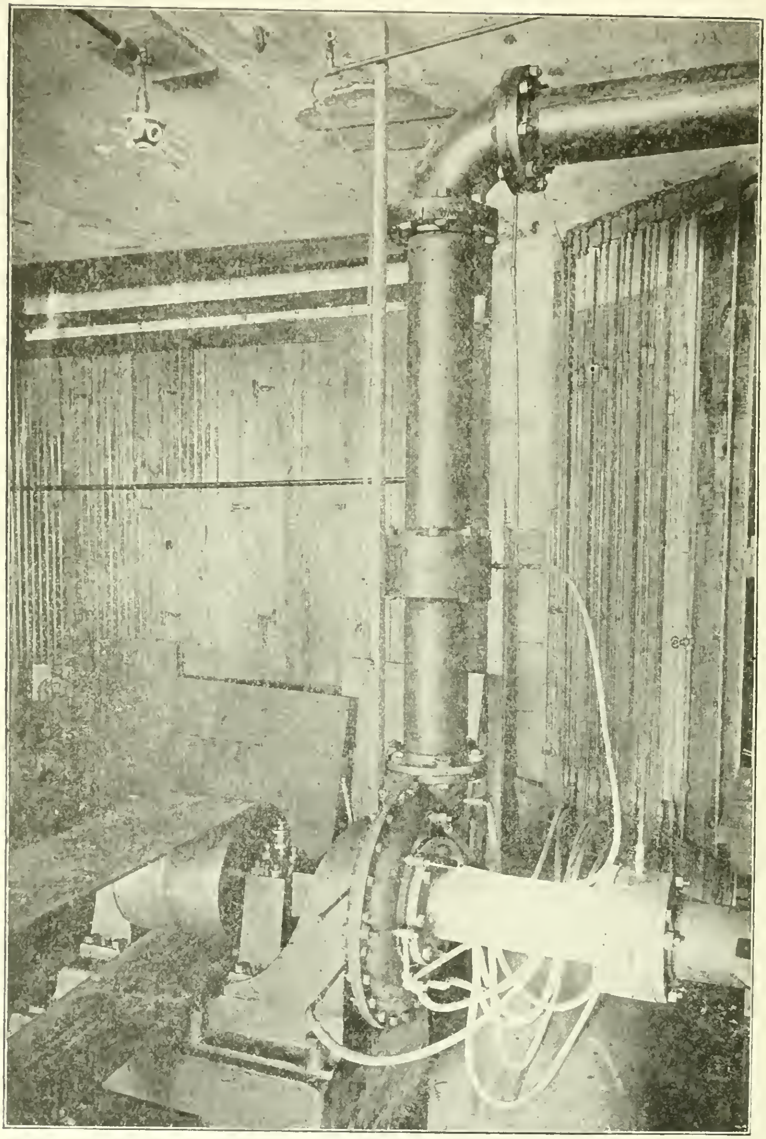


PLATE VI—VIEW SHOWING SIX INCH HORIZONTAL CENTRIFUGAL PUMP AND ARRANGEMENT OF GAGES.

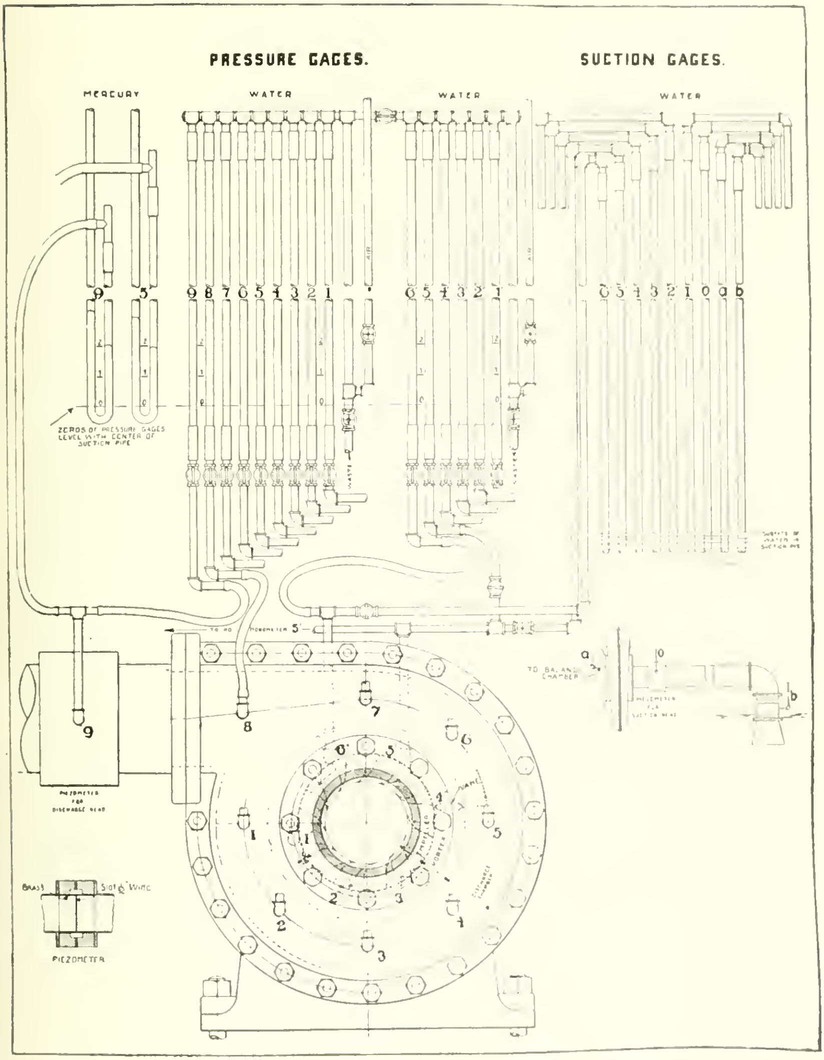


Plate VII—Experiments with a 6-inch Horizontal Centrifugal Pump.

Sketch Showing Arrangement of Water and Mercury Gages.

Nos. 1–8 respectively. The piezometer for measuring discharge head, termed point No. 9, is connected to both mercury manometer No. 9 and to water gage No. 9. Provision was made for the admission of air, under a common pressure, to the tops of the water gages, so that each water column was depressed an equal amount, and by adjustment of the air pressure could be kept within the desired range. The combination thus formed a differential water gage, the variations in pressure being determined from the readings of the water gages. The absolute pressure at each of the points Nos. 1–8 was determined by adding to each of the readings of the gages Nos. 1–8, the difference between the reduced reading of mercury manometer No. 9 and water gage No. 9.

It should be noted that the center of the pump and center of the suction pipe were assumed as a plane of reference, and the zeros of all mercury manometers and water gages for measuring pressure were adjusted to this level. The reduced readings of the mercury manometer and of the water gages, corrected as stated when subjected to air pressure, represented the heights of the piezometric water columns above the center of the pump, at the various points where measurements were taken.

The points chosen in the vortex chamber for the measurement of pressures, indicated on Plate VII by Nos. 1′–6′, were located three-eighths inches outside of the inner edge of the vortex. The piezometric connections were made by holes about three-sixteenths inches in diameter, normal to the surface of the vortex. Connections to water gages Nos. 1′–6′ were made by rubber tubing as shown. In order to determine the absolute pressure at points Nos. 1′–6′ in the vortex, when the water columns were depressed by being subjected to air pressure, connection was made from point No. 5′ to mercury manometer No. 5′. The absolute pressure at each of the points Nos. 1′–6′, was then determined by adding to each of the readings of the gages Nos. 1′–6′, the difference between the reduced reading of mercury manometer No. 5′ and water gage No. 5′.

For low heads pumped against, and the large discharges, the pressures at points Nos. 1′–6′ were less than atmospheric and provision was made for measuring the pressure by connections to the suction water gages as shown. The height the water was lifted in the tubes above the surface of the water in the suction pit thus represented the pressure, less than atmospheric, at the point of attachment of the tube to the vortex.

Suction water gages termed (0), (a) and (b), Plate VII, were used respectively for measuring the suction head at entrance to the pump, pressure in the balance chamber of the pump, and pressure at point (b), just above the surface of the water in the suction pit.

Electrical Instruments

The electrical instruments used for measuring the power delivered to the electrical motor, were the most accurate and reliable procurable, and consisted of a Laboratory Standard Voltmeter and a Laboratory Standard Ammeter, each of the Weston make. These instruments were carefully compared with similar laboratory standard instruments belonging to the Department of Electrical Engineering of the University, which had been calibrated by means of a potentiometer. These instruments have a guaranteed limit of error, not to exceed one-tenth of one per cent for the ordinary range of temperature. The reason for using such expensive instruments, in place of the ordinary instruments of the portable type, was the certainty that the experimental work would be continued several years, and it was desired to avoid the necessity and uncertainty due to repeated calibrations.

In order to protect the instruments from magnetic influence from the electric motor which was about five feet distant, each instrument was completely enclosed, except directly over the reading arc, by a heavy cast iron case having a thickness of metal of about one and one-half inches.

Pressure and Vacuum Gages

The pressure and vacuum gages, used for measuring discharge head and suction head, were Crosby water test gages of the Bourdon type, with a three inch dial. The limit of accuracy of making the zero setting of the needle with these gages was about one foot, and the results were accordingly used only as a check on the determination of heads by more reliable methods.

SPEED OF PUMP

The speed of the pump shaft was determined in all cases by a revolution counter of the positive type. Provision was made so that it was impossible for the point of the counter to slip in the end of the shaft. The time interval used for taking speed with the revolution counter was one minute, a stop watch of known small error being used for the purpose.

CALIBRATION OF 25 H. P. ELECTRICAL MOTOR, BELT CONNECTED TO SIX INCH HORIZONTAL CENTRIFUGAL PUMP

This motor was a direct current, shunt wound, variable speed motor, rated at 25 H. P., made by the Northern Electrical Manufacturing Company of Madison, Wisconsin. It was operated on a 500 volt circuit, and speeds could be varied from 650 to 1050 revolutions per minute. To the armature shaft was keyed a 16-inch pressed paper pulley, which was connected to the 14-inch pulley on the pump shaft by means of a twelve inch double strength leather belt. In order to determine the actual horse power delivered to the impeller of the pump, it was necessary to run the pump shaft at the ordinary speeds and loads, and absorb the power by means of a Prony brake, as shown by the photograph, Plate VIII. This brake was of the solid wood block type, and was applied to a cast iron pulley sixteen inches in diameter and four inch face. The brake had a twenty-four inch lever arm, and was provided with a knife edge for transmitting pressure to a tested platform scale. The wooden blocks of the brake were of maple, and were thoroughly saturated by boiling in linseed oil.

The impeller of the pump was removed from the pump shaft previous to the starting of the experimental work with the brake. Considerable difficulty was experienced in maintaining a steady poise of the scale beam, owing to the fluctuations in voltage and current in the 500 volt commercial power circuit which it was necessary to use. The voltage varied from 400 to 500 volts on different days. While instantaneous changes of as much as ten amperes sometimes occurred in current, yet by taking averages of about eight simultaneous readings of the voltmeter and ammeter, and discarding observations where fluctuations of the current exceeded about one ampere during the set of observations, quite consistent results were obtained. During each set of observations, the scale beam was kept balanced by means of an adjusting screw on the brake. The surface of the brake pulley was kept from heating, by maintaining in the usual manner a circulation of cold water on the inside

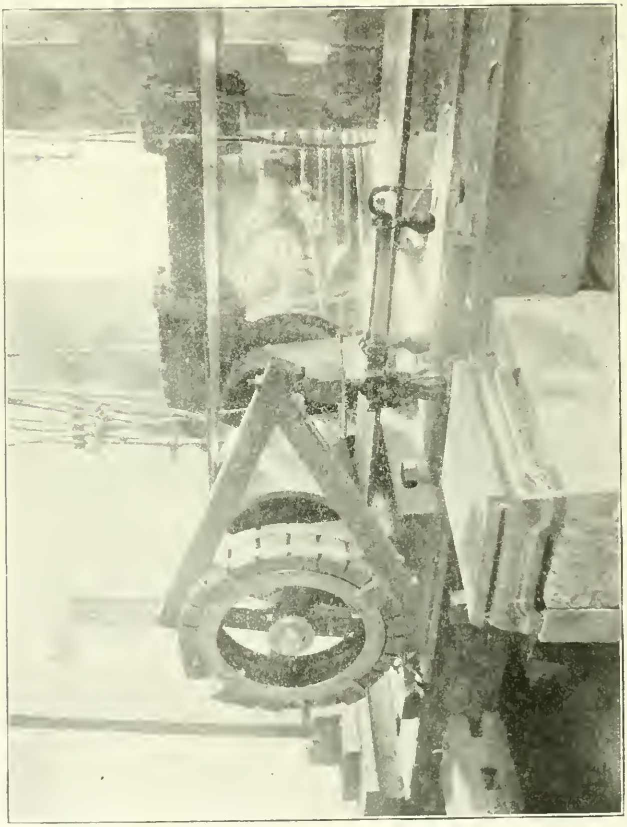


PLATE VIII—VIEW SHOWING FORM OF PRONY BRAKE USED.

surface of the pulley. The pump shaft was run at the two speeds 1,100 and 1,300 revolutions per minute, and values of the brake horse power determined, which corresponded to the electrical horse power or power delivered to the motor. A sufficient number of observations were taken at each speed to cover the required range of load, and to show the effect of change of voltage. Previous to the tests with the Prony brake, the motor and pump were run light and values of the power required were determined for various voltages.

Tables I and II are summary sheets showing the results of the observations for the two speeds. Each of the power readings of voltmeter and ammeter represents the mean of eight readings. The observed weight on the platform scale included a small weight resulting from the unbalanced arm of the brake. This unbalanced weight was determined by balancing the brake, when placed in a horizontal position, over a straight edge passing through the diameter of the sixteen inch circle and perpendicular to the line from the center of the circle to the knife edge. This unbalanced weight of the arm, found to equal 1.3 pounds, acting through the line of the knife edge, was subtracted from the observed weight on the scale and the remainder was termed the "Corrected weight on scale."

The electrical horse power, or power supplied to the motor, was obtained by dividing the product of the amperes and volts by 746.

The brake horse power termed "Horse power input" was determined by the formula

$$\text{B. H. P.} = \frac{n \cdot 2\pi l W}{33000},$$

where n = revolutions per minute, l = 2.00 = length of brake arm in feet, and W = corrected weight on scale in pounds.

Plate IX shows graphically the results of the brake test of the 25 H. P. motor, lines having been drawn to represent the results for three values of the voltage 400, 450 and 500. Each of the separate sets of observations is shown by circles, while the figures inside the circles represent one-tenth the value of the voltage. The ordinates "Brake horse power," represent the power that would be delivered to the impeller of the pump for certain values of the "Electrical horse power."

For a check on the results obtained by the above method of

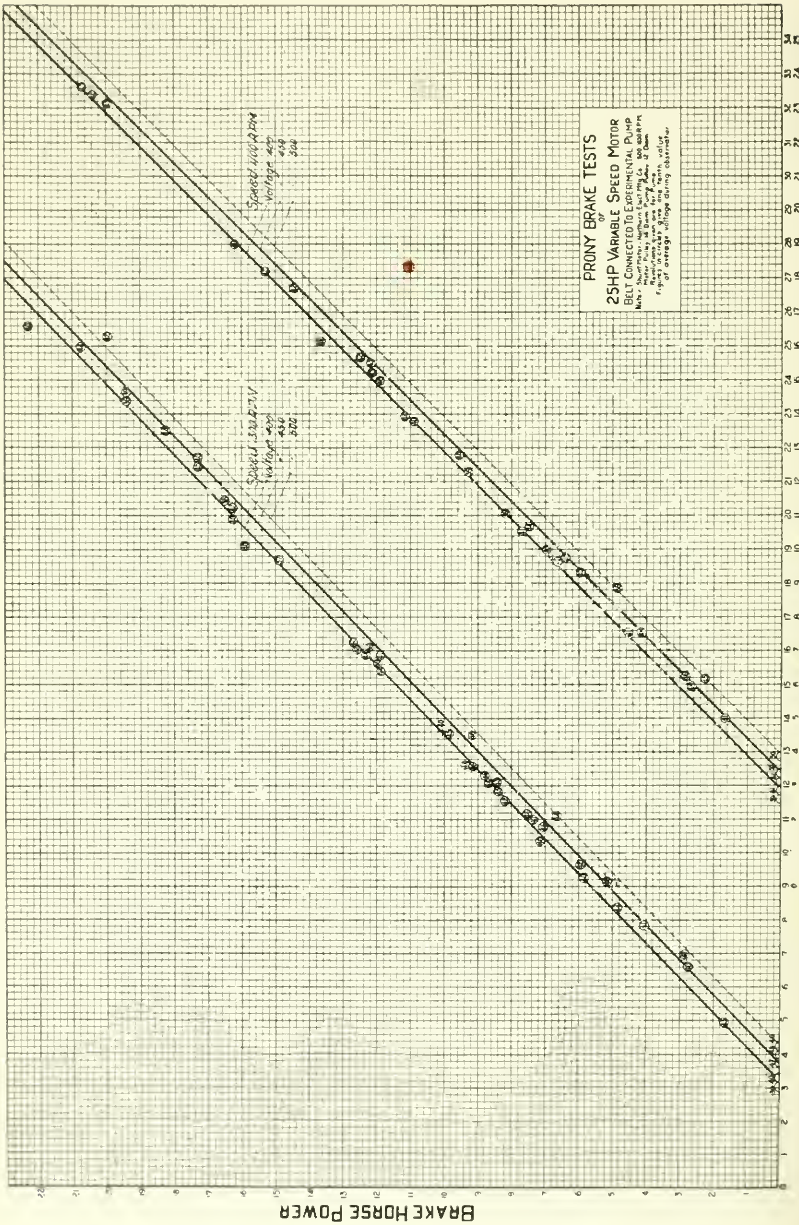


PLATE IX—EXPERIMENTS WITH A 6-INCH HORIZONTAL CENTRIFUGAL PUMP.

determining the power input to the pump, the value of the field current was measured in some cases (See Tables XIV–XVII), and values of the power input determined by the "Stray power method" (See Part I of Investigation of Centrifugal Pumps, page 480). The resistance of the armature including brush contacts, brushes and leads was 0.17 ohms, cold. The results by the two methods agreed within a few per cent, and showed that the values used were sufficiently accurate for the purpose in view.

TABLE I.

Summary Sheet: Calibration of 25 Horse Power Electrical Motor Belted to Six-Inch Horizontal Centrifugal Pump.

Diameter of Pulley on Motor = 16 inches.
Diameter of Pulley on Pump = 14 inches.
Speed of Pump = 1,100 Revolutions per Minute.

Time.		Reference No.	Revolutions per minute.	Power Reading.		Electrical horse power.	Corrected weight on scale.	Brake horse power.
				Average current	Average E. M. F.			
			R. P. M.	Amps.	Volts.	E. H. P.	Lbs.	B. H. P.
July 5..........	5:30	[1]1	1.115	5.74	486.8	3.74	....	....
	5:35	2	1.117	5.69	503.7	3.83	....	....
	5:40	3	1.121	5.77	491.4	3.81	....	....
	5:00	4	1.093	5.64	400.8	3.03	....	....
	11:45	5	1.086	5.29	393.2	2.78	....	....
	11:50	6	1.097	5.26	408.4	2.86	....	....
June 22..........	9:57	7	1.115	10.30	447.5	6.16	5.4	2.28
	10:27	8	1.110	14.3	463.5	8.86	11.5	4.87
	10:33	9	1.120	15.5	418.3	9.32	13.9	5.97
	10:40	10	1.112	19.2	412.0	10.60	18.0	7.65
	10:47	11	1.125	21.9	435.9	12.80	22.2	9.55
	10:53	12	1.116	25.6	402.0	13.80	25.6	10.90
	10:57	13	1.121	26.2	427.3	15.00	28.7	11.90
	11:00	14	1.125	29.3	111.0	16.15	21.9	13.66
	11:28	15	1.135	35.4	401.4	19.00	37.2	16.30
	11:35	16	1.148	32.0	424.5	18.20	34.7	15.30
	11:57	17	1.134	17.3	432.7	10.01	16.0	6.96
	12:03	18	1.098	16.5	441.5	9.75	15.3	6.45
	12:07	19	1.099	12.7	443.5	7.55	9.9	4.56
	12:15	20	1.110	10.1	462.4	6.25	6.6	2.82
June 23..........	2:57	21	1.108	12.9	389.7	6.73	8.4	3.55
	3:05	22	1.109	9.1	408.4	4.98	3.9	1.65
	3:25	23	1.102	17.9	444.2	10.65	17.9	7.54
	3:34	24	1.100	24.6	423.2	13.95	26.6	11.18
	4:20	25	1.117	23.6	389.5	12.30	21.7	9.28
	4:35	26	1.092	21.4	387.5	11.08	19.6	8.19
	4:40	27	1.992	17.6	409.4	9.65	15.9	6.65
	4:45	28	1.095	13.7	409.8	7.53	10.8	4.54
	4:55	29	1.108	10.2	433.5	5.92	6.3	2.68
July 3..........	10:30	30	1.142	28.2	415.6	15.70	28.6	12.50
	10:50	31	1.150	26.9	431.1	15.52	27.6	12.20
	11:00	32	1.155	26.7	426.4	15.25	27.4	12.15
	11:15	33	1.134	31.4	420.9	17.70	33.3	14.45
	12:00	34	1.140	40.2	430.1	23.15	45.7	19.96
	12.05	35	1.140	41.1	424.7	23.40	45.8	20.40
	12:10	36	1.140	41.4	426.8	23.60	47.5	20.70

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[1] Reference Nos. 1-6, prony brake removed, motor and pump shaft running light.

TABLE 11.

SUMMARY SHEET: CALIBRATION OF 25 HORSE POWER ELECTRICAL MOTOR BELTED TO SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

Diameter of Pulley on Motor=16 inches.
Diameter of Pulley on Pump=14 inches.
Speed of Pump=1300 Revolutions per minute.

Time.		Reference No.	Revolutions per minute.	Power Readings.		Electrical Horse Power.	Corrected weight on scale.	Brake Horse Power.
				Average Current	Average E. M. F.			
			R. P. M.	Amps.	Volts.	E. H. P.	Lbs.	B. H. P.
July 14..........	12:00	[1]1	1.308	5.90	393.6	3.11	....	....
	11:55	2	1.307	5.98	402.5	3.23	....	....
July 5........ ...	5:15	3	1.309	6.27	469.8	3.95	....	....
	4:40	4	1.313	6.51	448.0	3.91	....	.....
	4:35	5	1.300	6.52	457.2	4.00	....	....
June 25..........	4:43	6	1.303	8.7	426.1	4.97	3.4	1.69
	5:05	7	1.314	14.1	440.8	8.34	9.5	4.83
	5:10	8	1.314	15.8	451.4	9.55	12.2	6.14
	5.20	9	1.317	18.3	455.0	11.14	14.9	7.51
	5:25	10	1.315	20.1	456.0	12.30	17.4	8.80
June 26..........	11:27	11	1.277	12.2	404.0	6.60	5.6	2.74
	11:27	12	1.293	14.2	412.0	7.82	8.2	4.07
	11:27	13	1.317	17.0	424.0	9.65	11.8	5.95
	12:10	14	1.304	17.2	402.2	9.25	11.7	5.85
	12:10	15	1.319	19.3	400.8	10.35	14.1	7.14
	2:00	16	1.342	25.5	399.0	13.69	19.5	10.00
	3:25	17	1.315	29.1	416.5	16.25	25.2	12.70
	3.40	18	1.315	35.7	398.0	19.10	21.6	15.90
	5:45	19	1.312	25.9	444.0	15.40	23.6	11.90
June 27..........	4:18	20	1.318	21.1	428.6	12.10	16.7	8.42
	4:40	21	1.330	20.3	425.2	11.55	16.1	8.20
	4:40	22	1.335	20.4	432.1	11.82	16.4	8.40
	5:15	23	1.337	20.4	443.0	12.10	17.0	8.70
June 28..........	9:15	24	1.312	11.0	469.0	6.93	5.7	2.83
	9:25	25	1.328	14.7	462.6	9.13	10.1	5.15
	9:30	26	1.325	17.6	465.0	10.98	14.5	7.35
	9:35	27	1.327	17.3	464.0	10.78	13.8	7.03
	9:35	28	1.330	21.5	437.2	12.60	18.4	9.36
	10:10	29	1.326	22.5	448.3	13.53	19.3	9.84
	10:25	30	1.318	28.4	421.7	16.05	25.0	12.60
	10:25	31	1.331	26.9	441.5	15.91	24.2	12.30
	10:50	32	1.335	37.4	372.3	18.68	29.2	14.90
	12:05	33	1.340	38.4	437.0	22.50	35.6	18.25
	12:05	34	1.340	35.9	441.5	21.45	33.7	17.30
	12:05	35	1.313	43.7	424.1	24.90	41.3	20.80
	12:05	36	1.340	42.6	437.5	25.00	40.4	20.75
June 30..........	10:10	37	1.337	16.8	494.0	11.10	13.0	6.67
	10:55	38	1.337	21.9	459.7	13.50	17.9	9.17
	10:18	39	1.323	37.1	399.3	19.89	32.1	16.27
	10:30	40	1.323	35.6	424.8	20.25	32.1	16.28
	12:00	41	1.308	39.6	385.2	20.41	33.0	16.50
July 2...........	4:20	42	1.326	23.9	421.5	13.50	19.4	9.88
	4:37	43	1.340	40.0	405.0	21.70	33.7	17.30
	5:25	44	1.323	47.2	403.6	25.58	43.9	22.30
July 3......	9:40	45	1.355	44.8	391.4	23.50	37.2	19.40
	10:10	46	1.329	30.7	391.0	16.10	24.0	12.22
	10:30	47	1.333	29.0	407.8	15.85	23.3	11.90
	10:40	48	1.348	29.2	401.7	15.70	23.1	11.95
	10.45	49	1.343	45.5	386.0	23.55	36.4	19.40

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[1] Reference Nos. 1—5, prony brake removed. motor and pump shaft running light.

CALIBRATION OF 50 H. P. ELECTRIC MOTOR, BELT CONNECTED TO SIX INCH HORIZONTAL CENTRIFUGAL PUMP

This motor was a shunt wound variable speed motor, rated at 50 H. P., made by the Northern Electrical Manufacturing Company. The motor was operated on a 500 volt circuit and speeds could be varied from 500 to 1,000 revolutions per minute. To the armature shaft was keyed a 28 inch pulley, which was connected to the 14 inch pulley on the pump shaft by means of a twelve inch double strength leather belt.

The same Prony brake and general method of calibration was used for this motor as for the 25 H. P. The pump shaft was run at the three speeds, 1,100, 1,300 and 1,465 revolutions per minute. Table III is a summary sheet showing the results for the three speeds. Plate X shows graphically the results of the brake test of the 50 H. P. motor. The variation in brake horse power for a given electrical horse power, due to a variation in voltage, was very slight for this motor. An attempt was made to determine this variation but with little success, and lines representing only average results for each speed have been drawn.

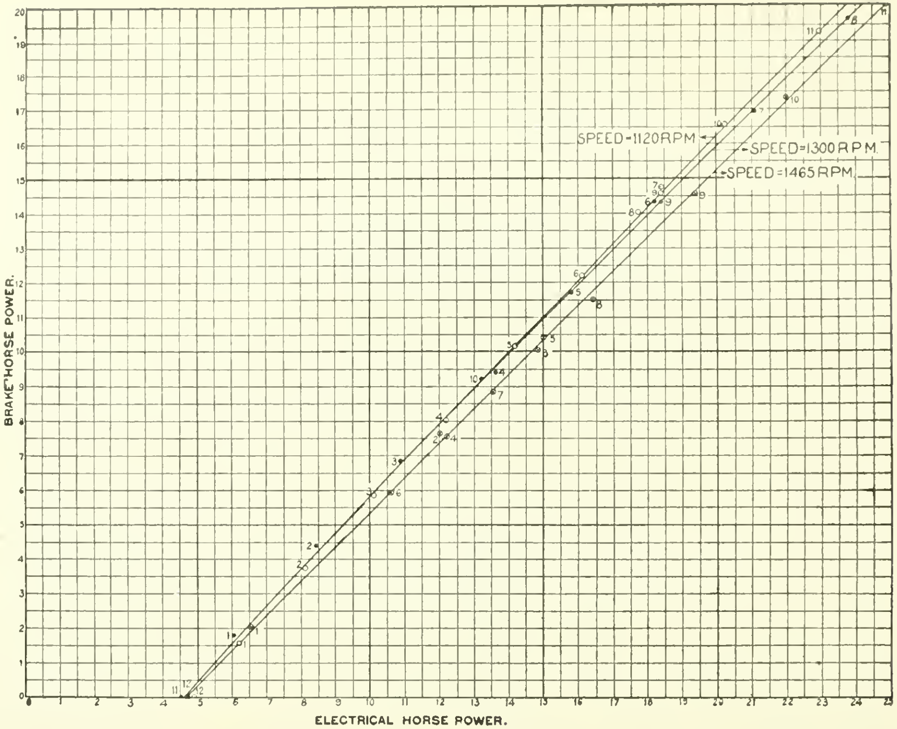


Plate X—Experiments with a 6-inch Horizontal Centrifugal Pump.

Prony Brake Tests of 50 H. P. Variable Speed Motor.

TABLE III.

SUMMARY SHEET; CALIBRATION OF 50 HORSE POWER ELECTRICAL MOTOR BELTED TO SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

Diameter of pulley on motor = 28 inches.
Diameter of pulley on pump = 14 inches.

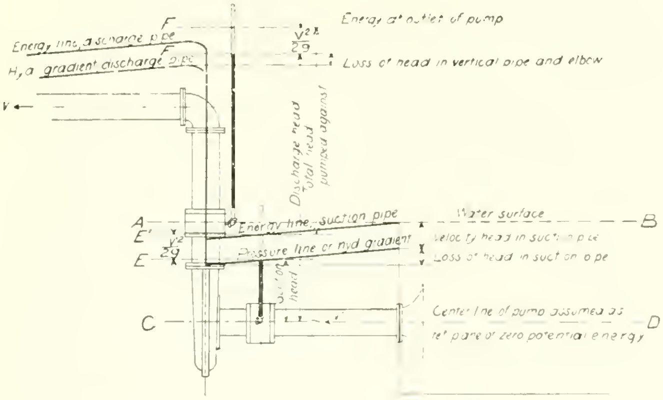
Time.		Reference No.	Revolutions per minute.	Power readings.		Electrical horse power.	Corrected weight on scale.	Brake horse power.
				Average current.	Average E. M. F.			
			R. P. M.	Amps.	Volts.	E. H. P.	Lbs.	B. H. P.
SPEED OF PUMP = 1120 REVOLUTIONS PER MINUTE.								
March 30........	9:27	1	1,121	10.5	442.6	6.24	3.7	1.58
	9:37	2	1,120	13.9	435.8	8.13	8.7	3.72
	9:53	3	1,120	17.5	430.8	10.10	13.7	5.85
	10:00	4	1.130	21.4	426.9	12.26	18.7	8.05
	10:13	5	1.126	25.2	418.5	14.16	23.7	10.18
	10:25	6	1.113	29.3	410.6	16.10	28.7	12.18
	10:35	6	1,142	34.4	397.1	18.40	33.7	14.70
	10:43	8	1.092	34.1	388.3	17.75	33.7	14.00
	10:52	9	1.132	34.0	403.7	18.40	33.7	14.55
	10:58	10	1,120	38.1	396.0	20.22	38.7	16.52
	11:15	11	1,151	43.0	398.2	22.95	43.7	19.20
March 31........	2:48	12	1.151	7.72	467.8	4.84	....	....
SPEED OF PUMP = 1300 REVOLUTIONS PER MINUTE.								
March 3.........	11.45	1	1.279	10.3	437.2	6.03	3.7	1.80
	11:55	2	1.327	14.5	433.3	8.41	8.7	4.38
	12:00	3	1,308	18.6	435.2	10.85	13.7	6.85
	12:05	4	1,322	23.5	432.3	13.60	18.7	9.42
	12:10	5	1,297	27.0	436.1	15.80	23.7	11.70
	12:18	6	1,307	32.0	424.7	18.22	28.7	14.30
	12:25	7	1.319	37.0	425.1	21.10	33:7	16.90
	12:30	8	1,328	42.4	418.2	23.80	38.7	19.60
	12:35	9	1.305	32.0	428.4	18.40	28.7	14.30
	12:40	10	1.291	22.4	438.9	13.20	18.7	9.20
March 31........	3:05	11	1,303	7.32	462.2	4.53	....	....
SPEED OF PUMP = 1.465 REVOLUTIONS PER MINUTE.								
March 30........	3:16	1	1,455	11.5	424.9	6.55	3.7	2.05
	3:30	2	1,459	21.7	411.5	12.00	13.7	7.63
	3:45	3	1,475	25.7	430.8	14.85	18.7	10.50
	5:20	4	1,439	19.5	467.3	12.20	13.7	7.48
	5:30	5	1,462	24.4	458.3	15.00	18.7	10.40
March 31........	9:45	6	1,460	18.1	435.8	10.60	10.7	5.93
	9:53	7	1,488	23.5	429.2	13.54	15.7	8.86
	10:00	8	1,464	28.5	429.0	16.42	20.7	11.50
	10:12	9	1,490	34.5	418.6	19.40	25.7	14.55
	10:20	10	1.480	40.0	412.4	22.00	30.7	17.30
	10:45	11	1.474	46.7	398.9	24.90	35.7	20.00
	3:20	12	1.463	7.8	467.3	4.67	....	....

DERIVATION OF EQUATION FOR TOTAL HEAD PUMPED AGAINST BY A CENTRIFUGAL PUMP

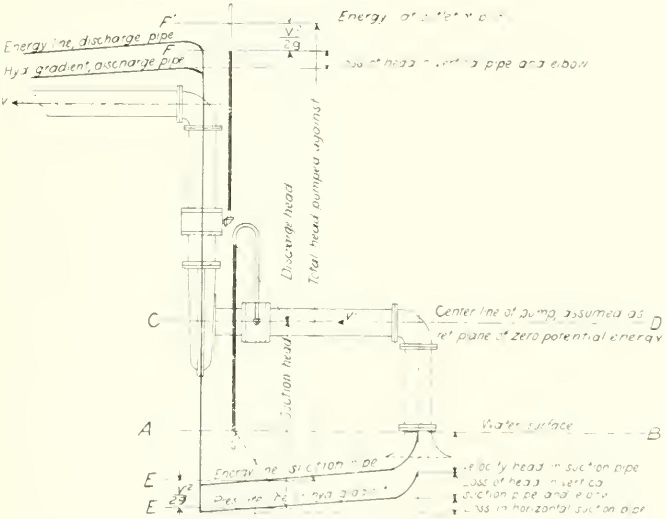
The energy of the water per unit weight at any point in passing through the pump, is equal to the sum of the separate energies, due to position, pressure and velocity. The horizontal plane, through the center of the impeller of the pump, may be conveniently taken as the plane of reference of zero potential energy. The total head pumped against, or developed by the pump, is equal to the difference between the energy of the water per unit weight at the outlet of the pump, and the energy of the water per unit weight at the inlet to the pump. If a pressure gage is connected to the discharge pipe, at or near the outlet of the pump, and placed at the same elevation as the point corresponding to which the total energy is desired, the energy due to position will be represented by the height of the center of the pressure gage above the center of the pump, or plane of reference; and the energy due to pressure will be represented by the reading of the gage. If a piezometer is connected to the discharge pipe at or near the outlet of the pump, and the pressure is measured by an open water column or mercury manometer, which have the zeros of their gages adjusted to the center of the pump, or plane of reference, the reading of these gages would represent the sum of the energies due to both position and pressure. The height of the actual or computed piezometric water column above the center of the pump, may conveniently be termed the discharge head, h_D. The total energy per unit weight of water at the outlet of the pump, is equal to the discharge head, h_D, plus the velocity head $\frac{v^2}{2g}$, due to the velocity, v, in the discharge pipe at the point of measurement of the discharge head.

Plate XI is a sketch showing two conditions, entrance to pump under suction and entrance to pump under pressure. AB represents the surface of the water in the suction pit; CF represents the discharge head, and CF′ the energy at the outlet of the pump.

The energy per unit weight of water at the entrance to the pump, is also made up of the sum of the energies due to position, pressure and velocity. The energy due to the velocity, v′, in


F
Energy line, discharge pipe
F
Hyd gradient discharge pipe
V
Energy at outlet of pump
$\frac{V^2}{2g}$
Loss of head in vertical pipe and elbow
Discharge head
Total head pumped against
A
E'
$\frac{V^2}{2g}$
E
Energy line, suction pipe
Pressure line or hyd gradient
Water surface
B
Velocity head in suction pipe
Loss of head in suction pipe
Suction head
C
Center line of pump assumed as ref plane of zero potential energy
D

ENTRANCE TO PUMP UNDER PRESSURE.


F'
Energy line, discharge pipe
F
Hyd gradient, discharge pipe
V
Energy at outlet of pump
$\frac{V^2}{2g}$
Loss of head in vertical pipe and elbow
Discharge head
Total head pumped against
C
V
Center line of pump, assumed as ref plane of zero potential energy
D
Suction head
A
Water surface
B
Energy line suction pipe
Pressure line hyd gradient
E
$\frac{V^2}{2g}$
E
Velocity head in suction pipe
Loss of head in vertical suction pipe and elbow
Loss in horizontal suction pipe

ENTRANCE TO PUMP UNDER SUCTION.

Plate XI—Experiments with a 6-inch Horizontal-Centrifugal Pump. Sketch to Accompany Discussion of Total Head Pumped Against.

the suction pipe is equal to the velocity head, $\frac{v'^2}{2g}$, and is always positive. The energy due to position will be either positive or negative, depending on whether the point of measurement of the suction head, i. e., location of piezometer in the suction pipe, is above or below the center of the pump. The energy due to pressure, measured at the location of the piezometer in the suction pipe, may be either positive or negative and depends on a variety of conditions; if the elevation of the water in the suction pit is greater than the elevation of the piezometer, by an amount exceeding the total loss of head plus velocity head in the suction pipe, then the energy at the piezometer due to pressure, will be positive, and vice versa. The sum of these energies due to position and pressure, may conveniently be termed the suction head, h_s. In Plate XI, the piezometer on the suction pipe is at the same elevation as the center of the pump, so the energy due to position is zero. In the upper half of the plate the energy due to pressure $= + CE = h_s$: while in the lower half, the energy due to pressure $= - CE = h_s$. The value $- CE$ is indicated in the plate as being measured by a suction water gage, in which the water is lifted to a height equal to CE by atmospheric pressure, when connection is made to the piezometer. A vacuum gage of the Bourdon type, placed at the elevation of the center of this piezometer, would also indicate the same value of the pressure, $- CE$. The values of pressure energy, or suction heads, $+ CE$ and $- CE$, are both seen to lie below the total energy lines, entrance to the pump, by the amount of the velocity head, $\frac{v'^2}{2g}$. It is evident, then, that the real or absolute value of the pressure of flowing water on a pipe, whether under a pressure greater or less than atmospheric, is decreased by an increase in the velocity of the water in the pipe; and also that readings of pressure and vacuum gages, or suitable gages connected to piezometers, simply indicate numerical values of these pressures above or below the atmospheric pressure[1].

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[1] This explanation has been given somewhat in detail in order to clear up a confusion that has recently arisen in regard to the interpretation of reading of gages on suction pipes. See Statement Am. Soc. C. E. Vol. LIV, Part C, page 405: "It is generally accepted that on a pipe flowing under pressure a piezometer will indicate all the head except the velocity head. On a suction pipe, however, a piezometer gives the total head on the pipe, including the velocity head."

The total energy per unit weight of water, at the entrance to the pump, therefore, is represented by

$$CE' = h_s + \frac{v'^2}{2g}$$

The total head pumped against, termed h, must be equal to the difference of the energies per unit weight of water at the outlet and entrance to the pump, and is given by the equation,

$$h = \left(h_D + \frac{v^2}{2g}\right) - \left(h_s + \frac{v'^2}{2g}\right),$$

or

$$h = h_D - h_s + \frac{v^2}{2g} - \frac{v'^2}{2g},$$

where h_s is negative for entrance to pump under suction, and positive for entrance to pump under pressure. If the discharge pipe and suction pipe are of the same diameter, the equation reduces to

$$h = h_D - h_s .$$

With the entrance to the pump under suction, Plate XI shows that the value of the suction head, h_s, is given by the reading of the suction water gage and numerically is equal to the difference of level between the water in the suction pit and the center of the pump, plus all losses of head in the suction pipe including entrance loss, plus the velocity head in the suction pipe at the entrance to the pump.

If it is not convenient to refer readings of discharge head and suction head to the center of the pump, an arbitrary plane of reference may be assumed, and account taken of the difference in level between the points of measuring the discharge head and suction head.

GENERAL METHOD OF MAKING OBSERVATIONS

Applying the equation for total head pumped against to the experimental results with the six inch pump, it is noted that the suction pipe and discharge pipe are of the same diameter; also that the readings of the discharge head and suction head, as explained under the description of piezometers, are referred to the center of the pump. For the entrance to the pump under suction, the total head pumped against is therefore equal to the sum of the numerical values of the discharge head and suction head. For entrance to pump under pressure, the total head pumped against is equal to difference of numerical values of the discharge head and suction head.

The discharge head was measured by an open mercury manometer, connected as shown on Plates III and IV and checked by reading of a Bourdon pressure gage. With the entrance to pump under suction, the suction head was measured by suction water gage No. 0, as shown on Plates III and XI, and checked by the reading of a vacuum gage; with entrance to pump under pressure, the suction head was measured by an open water gage as shown on Plate IV.

The head on the weir was measured by a hook gage, reading to ten thousandths of a foot, the hook being placed in a still water basin, as shown on Plates III and IV.

The speed of the pump was kept constant through all the ranges of head pumped against, the head being regulated by means of the six inch gate valve in the discharge pipe.

The length of each experiment, speed of pump and head pumped against remaining constant, varied from five minutes to one and one-half hours, usually lasting about one-half hour, the experiment being continued until certain that normal conditions of flow were taking place. The gate valve was then changed and the experiment made at some other head, the speed remaining the same. The head first pumped against was usually the lowest head obtainable (gate valve wide open), and this was increased in five feet intervals to the maximum head which the pump holds up without any delivery, the gate valve then being closed. The speed was then changed and another series of experiments made.

Each set of observations at any one head occupied an interval of from five to ten minutes. Two persons were necessary in taking the observations. While one observer was taking the speed of the pump, the other recorded the head on weir, discharge head and suction head of the pump. The power readings were then taken by both observers, eight simultaneous readings of the voltmeter and ammeter being taken in order to eliminate, as much as possible, the existing fluctuations in the power circuit. Readings of speed of pump, head on weir, discharge head and suction head were then repeated as quickly as possible, thus completing the one set of observations. Such auxiliary observations of pressures in the discharge chamber or vortex, were then taken as desired. The observations at the one head and speed were continued until certain that normal conditions of flow existed and sufficient data were obtained to definitely determine the forms of the curves of discharge and efficiency.

TABULATED RESULTS OF EXPERIMENTS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP

The following Tables IV, VI, VIII–XXII give a summary of the results of the actual observations with the pump having the circular case and the spiral case, under various conditions. Each of the values recorded for speed of pump, head on weir, discharge head, and suction head represents averages of two readings, while each of the values for power represents an average of eight readings. Readings of pressure in the discharge chamber and vortex are single determinations.

It was considered unnecessary to give the original data as taken, as average results, in some respects, would be better for reference. The original data have, however, been filed in the office of the Department of Hydraulic Engineering of the University, and are accessible to any one who desires to consult them.

Following each of the tables giving data in regard to the actual observations, will be found a summary sheet (see Tables V, VII, IX–XXIII) giving the results of the experiments with averages and computations for the previous observation sheet. The data of each summary sheet are shown graphically (see Plate XII) by the following curves:

1. Curve showing relation of total head pumped against to discharge.
2. Curve showing relation of total head pumped against to efficiency.
3. Curve showing relation of total head pumped against to horse power output.
4. Curve showing relation of total head pumped against to horse power input.

The power delivered to the pump was determined from the electrical horse power by means of the curves of calibration of the 25 H. P. and 50 H. P. electrical motors, and has been termed "brake horse power" or "horse power input." During the calibration, or brake tests, of the 25 H. P. and 50 H. P. electrical motors, a number of observations were made with the impeller in place on the pump shaft to determine if the friction of the impeller on the surrounding metal surface was measurable. This friction of the impeller was practically zero, so the "horse power input," represents power delivered to the impeller of the pump.

The horse power output is equal to the weight of water pumped per second, multiplied by the total head pumped against and the product divided by 550.

The efficiency of the pump was taken as equal to the ratio of the horse power output to horse power input.

The following is the order in which the data from the observations and summary sheets, showing results of computations, are given:

Table IV. Observation sheet; *discharge chamber circular* in form, entrance to pump under *suction*, air leakage condition No. 1, speed of pump 1,120 revolutions per minute.

Table V. Summary sheet for above, results platted on Plate XII.

Table VI. Observation sheet; *discharge chamber circular* in form, entrance to pump under *suction*, air leakage condition No. 1, speed of pump 1,275 revolutions per minute.

Table VII. Summary sheet for above, results platted on Plate XII.

Table VIII. Observation sheet; *discharge chamber circular* in form, entrance to pump under *suction*, air leakage condition No. 1, speed of pump 1,250 revolutions per minute.

Table IX. Summary sheet for above, results for efficiency not platted. Pressures in discharge chamber and vortex platted on Plate XVIII.

Table X. Observation sheet; *discharge chamber circular* in form, entrance to pump under *pressure*, speed of pump 1,120 revolutions per minute.

Table XI. Summary sheet for above, results platted on Plate XII.

Table XII. Observation sheet; *discharge chamber circular* in form, entrance to pump under *pressure*, speed of pump 1,300 revolutions per minute.

Table XIII. Summary sheet for above, results platted on Plate XII.

Table XIV. Observation sheet; *discharge chamber spiral* in form, entrance to pump under *suction,* slight air leakage condition No. 2, speed of pump 1,120 revolutions per minute.

Table XV. Summary sheet for above, results platted on Plate XIII.

Table XVI. Observation sheet; *discharge chamber spiral* in form, entrance to pump under *suction*, slight air leakage condition No. 2, speed of pump 1,290 revolutions per minute.

Table XVII. Summary sheet for above, results platted on Plate XIII.

Table XVIII. Observation sheet; *discharge chamber spiral* in form, entrance to pump under *pressure*, speed of pump 1,120 revolutions per minute.

Table XIX. Summary sheet for above, results platted on Plate XIV.

Table XX. Observation sheet; *discharge chamber spiral* in form, entrance to pump under *pressure*, speed of pump 1,300 revolutions per minute.

Table XXI. Summary sheet for above, results platted on Plate XIV.

Table XXII. Observation sheet; *discharge chamber spiral* in form, entrance to pump under *pressure*, speed of pump 1,500 revolutions per minute.

Table XXIII. Summary sheet for above, results platted on Plate XIV.

ABBREVIATIONS AND FOOT NOTES FOR TABLES

The following abbreviations and foot notes apply throughout the tables referred to above:

^{c} Represents water gages closed at top and subjected to air pressure.

$^{\circ}$ Represents water gages open at top.

† (Prefixed to time of making observation), represents discharge valve closed, and pump holding up given head without any water being delivered.

Signs (—), used in connection with water gages open at top, indicate pressures below atmospheric pressure, and is the pressure at the point of attachment of the water gage to the pump.

Signs (—), used in connection with water gages closed at top, indicate negative readings on the gage scale.

Readings of Bourdon pressure gage, for approximate determination of discharge head, have been corrected for difference of elevation between center of gage and center of suction pipe.

TABLE IV.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION.

(Air leakage condition No. 1.)

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS-SECTION CIRCULAR 3½" DIAMETER; THROAT OPEN, 3½" DIAMETER. VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛" x 2⅛"). IMPELLER, 12 VANES RADIAL WITH ENTRANCE CURVED. AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,120 REVOLUTIONS PER MINUTE.

TIME.	Average revolution of pump per minute.	POWER READINGS.		Average head on weir.	Suction head (inches of mercury).	Suction head water gage No. 0.	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.								READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, ⅜ INCHES OUTSIDE OF INNER EDGE OF VORTEX.					MERCURY MANOMETER FOR GAGE NO. 5.		Reading of water gage No. a, for bal. chamb.	Reading of water gage No. b.
		Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer. Left.	Mercury manometer. Right.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 1.	No. 2.	No. 3.	No. 5.	No. 6.	Left.	Right.		
	r. p. m.	a'p.	v'ts.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Feb. 26, 1906.						o		c			c	c	c	c	c	c	c	c	c	c	c	c	c				
4:50	1117	24.6	390.2	.4929	4.8	-4.6	13.5	4.9	2.08	1.08	5.2	5.6	5.7	5.2	4.2	2.8	1.0	3.9	6.8	5.0	3.5	3.2	2.0	1.70	1.36	.....	.....
5:00	1116	24.8	386.1	.4928	4.4	-4.6	13.7	4.4	2.08	1.07	4.5	4.9	5.2	4.5	3.7	2.2	0.4	3.4	6.1	4.2	2.3	2.2	1.2	1.71	1.38	.....	.....
5:05-5:07	1126	24.3	405.8	.4981	4.2	-4.6	14.0	5.4	2.08	1.08	5.5	6.0	6.3	5.5	4.6	3.2	1.5	4.4	6.5	4.9	3.3	2.7	1.3	.70	1.36	.....	.....
5:15	1120	24.5	401.8	.4967	4.0	-4.6	14.0	4.5	2.08	1.08	4.1	4.6	5.1	4.2	3.5	2.	0.2	3.5	6.7	5.1	3.6	2.6	1.7	1.69	1.37	.....	.....
5:20-5:22	1120	24.0	425.8	.5075	4.0	-4.7	14.5	4.7	2.10	1.06	4.3	4.7	5.1	4.6	3.4	3.3	0.3	3.7	7.0	5.4	3.8	2.9	1.9	1.71	1.36	.....	.....
Averages	1120	24.4	401.9	.4976	4.3	-4.6	13.9	4.8	2.08	1.07	4.7	5.2	5.5	4.8	3.9	2.7	0.7	3.8	6.6	4.9	3.5	2.7	1.6	1.7	1.37	.....	.....
March 5, 1906.						o		o			o	o	o	o	o	o	o	o	o	o	o	o	o	....	....	.....	.....
10:04-10:07	....	28.1	390.6	.6100	5.7	-6.3	3.8	4.2	1.69	1.49	5.2	5.9	6.9	6.2	5.3	3.	0.2	3.5	-2.7	-3.6	-3.4	-5.4	-11.7	....	....	.....	.....
10:15-10:18	1114	28.0	400.6	.6140	5.7	-6.4	3.8	4.1	1.69	1.49	5.2	5.9	6.8	6.4	5.5	3.9	0.2	3.5	-2.7	-3.7	-3.5	-5.6	-11.7	....	....	.....	.....
10:30	1114	28.2	394.8	.6092	5.5	-6.4	3.8	4.2	1.69	1.49	5.2	6.0	6.	6.4	5.1	3.	0.2	3.5	-2.8	-3.9	-3.8	-5.9	-12.6	....	....	.....	.....
10:40-10:42	1128	27.4	432.0	.6125	5.7	-6.4	3.8	4.2	1.70	1.48	5.3	6.	6.8	6.4	5.4	4.1	0.2	3.5	-2.6	-3.9	-3.8	-5.7	-12.8	....	....	.....	.....
10:55-10:57	1130	27.5	424.5	.6115	5.7	-6.4	3.8	4.2	1.69	1.50	5.4	6.0	6.9	6.4	5.4	3.9	0.3	3.5	-2.6	-3.6	-3.4	-5.5	-10.9	....	....	.....	.....
11:15-11:17	....	31.0	363.5	.6090	5.7	-6.5	3.8	4.2	1.69	1.49	5.4	6.1	7.	6.4	5.7	4.0	0.1	3.5	-2.5	-3.9	-3.9	-6.2	-13.3	....	....	.....	.....
Averages	1122	28.4	401.0	.6110	5.7	-6.4	3.8	4.2	1.69	1.49	5.3	6.0	6.9	6.4	5.4	4.0	0.2	3.5	-2.6	-3.8	-3.6	-5.7	-12.3	....	....	.....	.....

March 6, 1906.						o		c			c	c	c	c	c	c	c	c	c	c	c	c	c				
11:00-11:03	1080	22.9	399.6	.4976	4.0	-4.6	13.5	4.0	2.05	1.12	3.2	4.0	4.5	4.2	3.1	1.8	0.2	3.0	7.0	5.9	4.2	4.5	3.7	1.71	1.36	.....	.....
11:10-11:13	1120	24.1	409.2	.5048	4.0	-4.6	13.7	4.8	2.07	1.10	4.5	5.3	5.7	5.2	4.2	2.7	0.8	3.9	5.8	4.2	2.7	2.9	1.6	1.71	1.36	.....	.....
11:20-11:23	1135	25.3	393.6	.5055	4.0	-4.7	14.0	.0	2.07	1.08	3.7	4.6	5.0	4.3	2.5	1.8	0.	3.	5.7	4.4	2.6	2.7	1.7	1.7	1.36	.....	.....
11:33-11:36	1195	22.9	403.8	.4931	3.8	-4.6	13.0	4.3	2.03	1.12	3.7	4.4	4.9	4.6	3.6	2.1	0.5	3.3	6.3	4.5	3.5	3.4	2.4	1.69	1.37	.....	.....
11:40-11:43	1105	22.4	439.2	.4955	3.8	-4.6	13.5	4.9	2.06	1.10	4.5	5.3	5.9	5.2	4.3	2.8	1.1	3.9	5.1	4.8	2.2	2.3	1.1	1.71	1.36	.....	.....
11:45-11:48	1110	22.4	435.0	.4975	3.8	-4.6	13.5	5.0	2.04	1.10	4.9	5.6	6.0	5.4	4.4	3.1	1.3	4.0	5.3	3.8	2.3	2.2	1.2	1.71	1.36	.....	.....
Averages	1124	23.3	413.4	.4990	3.9	-4.6	13.5	4.5	2.05	1.10	4.1	4.9	5.3	4.8	3.7	2.4	0.6	3.5	5.9	4.6	2.9	3.0	2.0	1.71	1.36	.....	....
March 6, 1906.						o		c			c	c	c	c	c	c	c	c	o	o	o	o	o				
4:43-4:46	1101	23.5	430.6	.5362	4.0	-5.6	10.5	3.9	1.94	1.23	4.9	6.3	6.9	6.4	3.7	2.1	0.9	3.3	5.2	5.4	5.5	4.2	0.3	1.64	1.43	.....	.....
4:50:4:53	1102	23.6	425.6	.5378	4.0	-5.5	10.5	....	1.94	1.23	....	....	....	....	....	....	....	....	4.9	5.2	5.2	4.0	0.6	1.64	1.45	.....	.....
5:10-5:13	1110	23.4	450.6	.5424	4.0	-5.4	11.0	3.5	1.94	1.21	4.7	5.8	6.3	5.9	3.1	1.6	0.4	3.0	5.4	5.4	5.2	4.2	0.4	1.65	1.43	.....	.....
5:15-5:18	1110	23.5	460.2	.5460	4.0	-5.4	11.0	3.6	1.95	1.21	5.0	5.8	6.5	6.0	3.2	1.7	0.4	3.0	5.6	5.6	5.3	4.2	0.3	1.64	1.44	.....	.....
Averages	1106	23.4	441.8	.5406	4.0	-5.5	10.8	3.7	1.94	1.22	4.9	6.0	6.6	6.1	3.3	1.8	0.6	3.1	5.3	5.4	5.3	4.2	0.4	1.64	1.44	.....	.....
March 7, 1906.						o		c			c	c	c	c	c	c	c	c	c	c	c	c	c				
3:20-3:23	1111	16.6	371.4	.2862	2.4	-2.8	19.5	3.3	2.28	0.88	2.3	2.4	2.6	2.5	0.9	0.9	0.7	2.8	5.0	2.8	3.0	4.6	4.7	2.03	1.02	.....	.....
3:30-3:33	1117	16.6	372.2	.2843	2.4	-2.8	19.0	3.4	2.28	0.88	2.3	2.5	2.9	2.7	0.9	0.8	0.7	3.0	5.4	2.9	3.2	4.9	5.0	2.03	1.02	.....	.....
3:40-3:43	1116	16.0	385.4	.2874	2.4	-2.8	20.0	3.6	2.28	0.87	2.5	2.8	3.0	2.9	1.1	.1	0.9	3.1	5.6	3.2	3.7	5.1	5.3	2.04	1.03	.....	.....
3:50-3:54	1120	16.2	367.1	.2868	2.4	-2.8	20.0	3.8	2.28	0.87	2.8	3.0	3.2	3.1	1.3	1.2	1.1	3.2	6.0	3.4	4.0	5.4	5.5	2.03	1.02	.....	....
4:00-4:03	1137	16.0	403.8	.2922	2.4	-2.8	20.0	3.9	2.30	0.85	2.9	3.1	3.4	3.2	1.4	1.4	1.2	3.5	4.5	2.1	2.5	4.	4.2	2.05	1.02	.....	.....
4:10-4:13	1131	16.1	377.4	.2887	2.4	-2.8	20.0	4.1	2.26	0.90	3.0	3.2	3.4	3.3	1.6	1.4	1.3	3.6	4.8	2.4	2.8	4.3	4.4	2.04	1.03	.....	.....
4:20-4:23	1126	16.0	389.2	.2890	2.3	-2.8	20.0	4.2	2.29	0.87	3.2	3.4	3.6	3.5	1.7	1.8	1.5	3.7	5.2	2.6	3.1	4.7	4.6	2.05	1.03	.....	.....
4:30-4:33	1129	16.0	396.4	.2889	2.3	.9	20.0	4.2	2.29	0.85	3.3	3.4	3.8	3.7	1.8	1.7	1.6	3.7	3.7	1.2	1.5	3.0	3.1	2.05	1.01	.....	.....
4:40-4:43	1118	16.0	403.0	.2904	2.3	-2.9	20.0	4.7	2.30	0.82	3.5	3.7	3.9	3.9	2.0	2.0	1.9	4.1	4.0	1.4	1.9	3.6	3.6	2.05	1.02	.....	.....
Averages	1123	16.2	385.1	.2882	2.4	-2.8	19.8	3.9	2.28	0.87	2.9	3.1	3.	3.2	1.4	1.5	1.2	3.4	4.9	2.4	2.9	4.4	4.5	2.04	1.02	.....	.....
March 7, 1906.						o		c			c	c	c	c	c	c	c	c	c	c	c	c	c				
†5:20	1119	7.1	486.0	.0000	2.0	-2.6	16.0	2.4	2.14	1.02	2.2	2.2	2.2	2.2	2.2	2.2	2.3	2.3	4.2	4.1	3.9	4.4	4.4	2.09	0.98	.....	.....
April 9, 1906.						o		o			o	o	o	o	o	o	o	o	o	o	o	o	o			o	o
4:15	1127	35.8	323.6	.6062	5.0	-6.4	3.7	4.2	1.69	1.50	5.1	5.5	6.3	6.2	5.2	3.4	-0.8	3.6	-3.0	-4.4	-4.3	-8.0	-17.7	....	....	-2.9	-3.7
4:28-4:33	1150	33.9	362.2	.6120	5.0	-6.4	3.7	4.2	1.70	1.49	5.0	5.3	6.2	6.1	5.3	3.4	-1.2	3.6	2.7	-4.3	-4.5	-8.9	-19.2	....	....	-2.8	3.8
4:45-	1137	30.5	391.2	.6086	5.0	-6.3	3.5	4.2	1.69	1.49	5.5	5.9	6.6	6.5	5.7	3.8	-1.3	3.7	-2.9	-4.1	-4.1	-8.2	-18.6	....	....	2.9	-3.7
4:55-	1138	29.8	383.2	.6087	5.0	-6.4	3.6	4.2	1.69	1.49	5.4	5.8	6.6	6.4	5.6	3.7	1.3	3.5	-2.9	4.1	-4.0	7.4	-18.5	....	....	2.8	-3.7
Averages	1138	32.5	365.0	.6088	5.0	-6.4	3.6	4.2	1.69	1.49	5.2	5.6	6.4	6.	5.4	3.6	-1.2	3.6	-2.9	-4.2	-4.2	-8.1	-18.5	....	....	-2.9	-3.7
May 11, 1906.						o		c			c	c	c	c	c	c	c	c									
4:04-4:08	1122	25.6	410.0	.5545	4.6	-5.6	7.5	4.5	1.66	1.19	5.	5.8	6.	5.9	5.0	3.2	0.	3.9	.....	.....	.....	.....	.....	....	....	.....	.....
4:12-4:15	1124	24.2	410.6	.5080	4.1	-4.7	13.0	5.2	1.86	0.98	5.3	5.8	6.4	5.8	5.1	3.6	1.6	4.6	.....	.....	.....	.....	...	....	....	.....	.....
4:18-4:21	1121	23.4	402.8	.4805	3.7	-4.4	14.5	5.8	1.95	0.85	5.4	6.0	6.2	5.8	5.0	3.9	2.0	5.0	.....	.....	.....	.....	.....	....	....	.....	.....
4:25-4.28	1119	22.1	400.2	.4488	3.5	-4.5	17.0	4.6	2.05	0.76	3.7	4.1	4.2	3.6	3.2	2.0	0.3	3.6	.....	.....	.....	.....	.....	....	....	.....	.....
4:30-4:33	1120	20.2	409.2	.4033	3.0	-3.7	21.5	5.6	2.18	0.63	4.2	4.3	4.2	3.4	2.8	1.8	0.2	4.9	.....	.....	.....	.....	.....	....	....	.....	.....

TABLE IV—Continued.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION.

(Air leakage condition No. 1.)

TIME.	Average revolution of pump per minute.	POWER READINGS.		Average head on weir.	Suction head (inches of mercury).	Suction head water gage No. 0.	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER.								READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, ¾ INCHES OUTSIDE OF INNER EDGE OF VORTEX.					MERCURY MANOMETER FOR GAGE NO. 5.		Reading of water gage No. a. for bal. chamb.	Reading of water gage No. b.
		Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer.		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 1.	No. 2.	No. 3.	No. 5.	No. 6.	Left.	Right.		
									Left.	Right.																	
	r.p.m.	a'p.	v'ts.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
May 11, 1906.						o		c			c	c	c	c	c	c	c	c									
4:36-4:39	1146	18.4	412.8	.7578	2.8	.....	23.0	5.9	2.24	0.56	4.3	4.3	4.2	3.4	2.9	2.0	0.6	5.3	.....	.....	.....	.....	.....	.....	.....	.....	.....
4:43-4:46	1141	17.2	409.0	.3240	2.8	.....	23.5	5.9	2.28	0.54	4.2	4.2	4.1	3.4	2.9	2.2	1.0	5.3	.....	.....	.....	.....	.....	.....	.....	.....	.....
4:48-4:51	1157	15.1	412.6	.2758	3.9	.....	24.0	6.0	2.31	0.50	4.0	4.0	3.9	3.4	3.0	2.5	1.6	5.4	.....	.....	.....	.....	.....	.....	.....	.....	.....
4:54-4:57	1123	10.9	438.2	.1704	2.8	.....	23.0	5.5	2.23	0.56	3.5	3.5	3.5	3.3	3.2	3.0	2.8	5.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:03-5:06	1122	12.0	438.6	.2114	2.8	.....	23.5	5.6	2.26	0.54	3.7	3.5	3.5	3.3	3.1	2.8	2.4	5.1	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:09-5:12	1130	9.6	425.9	.1218	2.8	.....	22.5	5.0	2.23	0.58	3.4	3.4	3.4	3.	3.3	3.2	3.1	4.7	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:16-5:19	1141	8.5	472.1	.0877	2.8	.....	22.0	4.7	2.20	0.60	3.4	3.4	3.3	3.3	.3	3.3	3.3	4.5	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:20-5:23	1135	7.5	463.4	.0000	2.3	.....	20.0	4.0	2.10	0.70	3.4	3.4	3.4	3.4	3.5	3.5	.5	3.9	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:25-5:28	1102	7.4	463.1	.0000	2.3	.....	18.0	3.8	2.06	0.76	3.2	.2	3.3	3.	.3	3.4	3.4	3.8	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:30-5:33	1076	22.7	441.2	.5725	4.8	.....	3.0	3.5	1.51	1.33	4.6	5.1	6.2	5.9	4.9	2.9	.....	3.0	.....	.....	.....	.....	.....	.....	.....	.....	.....
5:43-5:46	1140	26.2	435.9	.5830	5.0	-6.1	3.5	3.7	1.51	1.33	4.7	5.2	6.0	5.6	4.7	2.8	.....	3.1	.....	.....	.....	.....	.....	.....	.....	.....	.....

Footnote:—For explanation of signs and symbols used in tables, see page 42.

TABLE V.

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION. (Air leakage, condition No. 1.)

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS-SECTION CIRCULAR, 3½" DIAMETER; THROAT OPEN, 3½" DIAMETER. VORTEX, RECTANGULAR IN CROSS-SECTION (1½"x2½"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED. AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1,120 REVOLUTIONS PER MINUTE.

TIME.		POWER READINGS.						DISCHARGE HEAD.								HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER.								HYDRAULIC GRADIENT ¾ INCHES OUTSIDE OF INNER EDGE OF VORTEX.							
																Water Gages.								Water Gages.							
	Reference No.	Revolutions per minute.	Average current.	Average E. M. F.	Electrical horse power.	Horse power input.	Suction head water gage No. 0.	Pressure gage.	Water gage No. 9.	Mercury manometer.	Total head.	Head on weir.	Discharge, cubic feet per second.	Horse power output.	Efficiency.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 1.	No. 2.	No. 3.	No. 5.	No. 6.	Mercury manometer for gage No. 5.	Balance chamber pressure, gage No. a.	Pressure at gage No. b.
		RPM	Amp.	Volts	EHP	BHP	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		HP	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Feb. 26, 1906. 4:50 5:22.	1	1,120	24.4	401.9	13.1	10.1	o 4.6	13.9	c 4.8	14.8	19.4	.4976	1.74	3.8	37.5	c 4.7 [1] 14.7	c 5.2 15.2	c 5.5 15.5	c 4.8 14	c 3.9 13.9	c 2.7 12.7	c 0.7 10.7	c 3.8 13.8	c 6.6 8.4	c 4.9 6.7	c 3.5 5.3	c 2.7 4.5	c 1.6 3.4	..... 4.5	....	....
March 5, 1906. 10:04 11:17	2	1,122	28.4	441.0	15.2	12.2	o 6.1	3.8	o 4.2	4.2	10.6	.6110	2.35	2.8	23.2	o 5.3	o 6.0	o 6.9	o 6.4	o 5.4	o 4.0	o 0.2	o 3.5	o −2.6	o −3.8	o −3.6	o 5.7	o −12.3	.....	.....	.....
March 6, 1906. 11:00 11:48	3	1,124	23.3	413.4	12.9	9.8	o 4.6	13.5	c 4.5	14.0	18.6	.4990	1.75	3.7	37.8	c 4.1 13.6	c 4.9 14.4	c 5.3 14.8	c 4.8 14.3	c 3.7 13.2	c 2.4 11.9	c 0.6 10.1	c 3.5 13.0	c +5.9 +7.7	c +4.6 +6.4	c +2.9 +4.7	c +3.0 +4.8	c +2.0 +3.8	..... +[illegible]	....	....
March 6, 1906 4:43 5:13	4	1,106	23.4	441.8	13.9	10.5	o 5.5	10.8	c 3.7	11.0	16.5	.5406	1.96	3.7	35.1	c 4.9 12.2	c 6.0 13.3	c 6.6 13.9	c 6.1 13.4	c 3.3 10.6	c 1.8 9.1	c 0.6 .9	c 3.1 10.4	o 5.3	o 5.4	o 5.3	o 4.2	o 0.4	4.2	....	....

[1] Values given are pressures in feet of water.

TABLE V.—Continued.

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

TIME.	Reference No.	Revolutions per minute.	POWER READING.		Electrical horse power.	Horse power input.	Suction head water gage No. 0.	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge, cubic feet per second.	Horse power output.	Efficiency.	HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER.								HYDRAULIC GRADIENT 1 INCHES OUTSIDE OF INNER EDGE OF VORTEX.						Balance chamber pressure, gage No. a.	Pressure at gage No. b.
																Water Gages.								Water Gages.							
			Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer.						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 1'.	No. 2'.	No. 3'.	No. 5'.	No. 6'.	Mercury manometer for gage No. 5.		
		RPM	Amp.	Volts	EHP	BHP	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		H P	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
March 7, 1906. 3:20—4:43...	[2]5	1,123	16.2	385.1	8.4	5.6	o —2.8	19.8	c 3.9	20.0	22.8	.2882	0.78	2.0	36.2	c 2. 19.0	c 3.1 19.2	c 3.3 19.4	c 3.2 19.3	c 1.4 17.5	c 1.5 1 .6	c 1.2 17.3	c 3.4 19.5	c 4.9 14.5	c 2.4 11.9	c 2.9 12.4	c 4.4 13.9	c 4.5 14.0	..... 13.9	....	....
March 7, 1906. †5:20........	[2]6	1,119	7.1	486.0	4.6	0.8	o —2.6	16.0	c 2.4	16.2	18.8	.0000	0.00	0.0	00.0	c 2.2 16.0	c 2.2 16.0	c 2.2 16.0	c 2.2 16.0	c 2.2 16.0	c 2.2 16.0	c 2.3 16.1	c 2.3 16.1	c 4.2 14.9	c 4.1 14.8	c .9 14.6	c 4.4 15.1	c 4.4 15.1	..... 15.1	....	....
April 9, 1906. 4:15—4:55...	7	1,138	32.5	365.0	15.8	13.1	o —6.4	3.6	o 4.2	4.2	10.6	.6088	2.32	2.8	21.4	o 5.2	o 5.6	o 6.4	o 6.3	o 5.4	o 3.6	o —1.2	o 3.6	o —2.9	o —4.2	o —4.2	o — .1	o —18.5	.....	o —2.9	o —3.7
May 11, 1906. 4:04—4:08...	8	1,122	25.6	410.0	14.1	11.0	o —5.6	7.5	c 4.5	7.6	13.2	.5545	2.03	3.0	27.6	c 5.0 8.1	5.8 8.9	6.3 9.4	5.9 9.0	5. 8.1	3.2 6.3	0.3 3.4	3.9 7.0	....	....	....	....	....	....	....	....
4:12—4:15...	9	1,124	24.2	410.6	13.3	10.2	o —4.7	13.0	c 5.2	13.0	17.7	.5080	1.79	3.6	35.2	c 5.3 13.1	5.8 13.6	6.4 14.2	5.8 13.6	5.1 12.9	3.6 11.4	1.6 9.4	4.6 12.4	....	....	....	....	....	....	....	....
4:18—4:21...	10	1,121	23.4	402.8	12.6	9.6	o —4.4	14.5	c 5.8	15.8	20.2	.4805	1.66	3.8	39.7	c 5.4 15.4	6.0 16.0	6.2 16.2	5.8 15.8	5.0 15.0	3.9 13.9	2.0 12.0	5.0 15.0	....	....	....	....	....	....	....	....

[2] Reference Nos. 5 and 6, amount of air leakage increased.

4:25—4:28...	11	1,119	22.1	400.2	11.9	8.9	o −4.5	17.0	c 4.6	18.3	22.8	.4488	1.50	3.9	43.6	c 3.7 17.4	4.1 17.	4.2 17.9	3.6 17.3	.2 16.9	2.0 15.7	0.3 14.0	3.7 17.4	....	....	....	....	....	....	....	....
4:30—4:33...	12	1,120	20.2	409.2	11.1	8.0	o −3.7	21.5	c 5.6	21.7	25.4	.4033	1.28	3.7	46.2	c 4.2 -0.3	4.3 20.4	4.2 20.3	3.4 19.5	2.8 18.9	1.8 17.9	0.2 16.3	4.9 21.0	....	....	....	....	....	....	....	....
4:36—4:39...	13	1,146	18.4	412.8	10.2	7.0	o −3.2	23.0	c 5.9	23.4	26.6	.3578	1.08	3.3	46.6	c 4.3 21.8	4.3 21.8	4.2 21.7	3.4 20.9	2.9 20.4	2.0 19.5	0.6 18.1	5.3 22.8	....	....	....	....	....	....	....	....
4:43—4:46...	14	1,141	17.2	409.0	9.4	6.3	o −3.2	23.5	c 5.9	24.2	27.4	.3240	0.94	2.9	46.4	c 4.2 22.5	4.2 22.5	4.1 22.4	3.4 21.7	2.9 21.2	2.2 20.5	1.0 19.3	5.3 23.6	....	....	....	....	....	....	....	....
4:48—4:51...	15	1,157	15.1	412.6	8.4	5.2	o 4.4	24.0	c 6.0	25.1	29.5	.2758	0.73	2.4	47.1	c 4.0 23.1	4.0 23.1	3.9 23.0	3.4 22.5	3.0 22.1	2.5 21.	1.6 20.7	5.4 24.5	....	....	....	....	....	....	....	....
4:54—4:57...	16	1,123	10.9	438.2	6.4	3.0	o 3.2	22.0	c 5.5	23.3	26.5	.1704	0.36	1.1	36.2	c 3.5 21.3	3.5 21.3	3.5 21.3	3.3 21.1	3.2 21.0	3.0 20.8	2.8 20.6	5.0 22.8	....	....	....	....	....	....	....	....
5:03—5:06...	17	1,122	12.0	438.6	7.0	3.7	c −3.2	23.5	c 5.6	23.9	27.1	.2114	0.49	1.5	40.7	c 3.7 22.0	3.5 21.8	3.5 21.8	3.3 21.6	3.1 21.4	2.8 21.1	2.4 20.7	5.1 23.4	....	....	....	....	....	....	....	....
5:09—5:12...	18	1,130	9.6	425.9	5.5	2.3	o 3.2	22.5	c 5.0	23.0	26.2	.1218	0.22	0.7	28.5	c 3.4 21.4	3.4 2..4	3.4 21.4	3.3 21.3	3.3 21.3	3.2 21.2	3.1 21.1	4.7 22.7	....	....	....	....	....	....	....	....
5:16—5:19...	19	1,141	8.5	472.1	5.4	1.7	o −3.2	22.0	c 4.7	22.3	25.5	.0877	0.13	0.4	22.2	c 3.4 21.	3.4 21.0	3.3 20.9	3.3 20.9	3.3 20.9	3.3 2 .9	3.3 20.9	4.5 22.1	....	....	....	....	.. ..	....	....	....
+5:20—5:23...	20	1,13	7.5	463.4	4.7	1.1	o −2.6	20.0	c 1.0	19.7	22.3	.0000	0.00	0.0	00.0	c 3.4 19.1	3.4 19.1	3.4 19.1	3.4 19.1	3.5 19.2	3.5 19.2	3.5 19.2	3.9 19.	....	....	....	....	....	....	....	... .
+5:25—5:28...	21	1,102	7.4	463.1	4.6	1.1	o 2.6	18.0	c 3.8	18.4	21.0	.0000	0.00	0.0	00.0	c 3.2 1 .8	3.2 17.8	3.3 17.9	3.3 17.9	3.3 17.9	3.4 18.0	3.4 18.0	3.8 18.4	....	....	....	....	....	....	....	....
5:30—5:33...	22	1,07	22.7	441.2	13.4	10.2	o −5.5	3.0	c 3.5	3.8	9.3	.5725	2.13	2.2	22.1	o 4.6	5.1	6.2	5.9	4.9	2.9	.....	3.0	.....	.....	.....	.....	.. ..	.....	.....	..
5:43—5:46...	23	1,140	26.	435.9	15.3	11.9	o −6.1	3.5	o 3.7	3.8	9.9	.5830	2.18	2.5	20.6	o 4.7	5.2	6.0	5.6	4.7	2.8	.....	3.1	.....	.....	.....	..	.....	.....	.....	.....

TABLE VI.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION. (Air leakage, condition No. 1.)

DISCHARGE CHAMBER. FORM CIRCULAR. CROSS SECTION CIRCULAR 3½" DIAMETER; THROAT OPEN 3½" DIAMETER. VORTEX: RECTANGULAR IN CROSS SECTION ("1⅛x2⅛") IMPELLER: 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1275 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head (inches of mercury).	Suction head water gage No. 0.	DISCHARGE HEAD.			
		Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer. Left.	Mercury manometer. Right.
	R.P.M	Amp.	Volts.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.
May 17, 1906.										
3:50	1273	33.0	383.2	.4860	4.9	......	26.0	......	2.34	0.47
4:00	1275	27.1	384.4	.3882	3.0	......	30.0	......	2.52	0.38
4:05	1282	30.4	385.4	.4460	3.3	......	27.7	......	2.80	0.74
4:10	1279	27.2	384.6	.4018	3.0	......	30.0	......	2.86	0.72
4:15	1274	26.0	378.4	.3857	2.9	......	30.5	......	2.88	0.70
4:20	1273	21.8	413.0	.3300	2.7	......	31.0	......	2.90	0.68
4:25	1275	29.4	405.8	.2942	2.5	......	32.0	......	2.94	0.63
4:30	1283	16.5	411.6	.2274	2.5	......	32.0	......	2.95	0.62
4:35	1279	14.0	419.0	.1798	2.4	......	31 0	......	2.92	0.64
4:40	1289	12.2	401.8	.1366	2.3	......	29.5	......	2.87	0.71
4:45	1293	12.1	407.4	.1204	2.3	......	29.5	......	2.87	0.70
†4:50—4:53.	1285	9.5	379.4	.0000	2.3	......	26.5	......	2.72	0.86
4:55—5:00	1252	39.3	340.2	.5858	5.0	......	15.8	......	2.35	1.26
5:05	1243	40.0	363.6	.6087	5.3	......	5.0	......	1.96	1.67
5:13	1259	42.1	353.0	.6189	5.3	......	4.0	......	1.90	1.72
5:20	1256	44.5	342.6	.6194	5.5	......	3.5	......	1.91	1.72

TABLE VII.

SUMMARY SHEET; RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

ENTRANCE TO PUMP UNDER SUCTION. (Air leakage, condition No. 1.)

Discharge Chamber, Form Circular, Cross-Section Circular, 3½" Diameter. Throat Open 3½" Diameter. Vortex. Rectangular in Cross-Section (1¼ x 2⅛"). Impeller, 12 Vanes: Radial With Entrance Curved. Area of Cross-Section of Waterway Practically Constant.

Speed of Pump 1275 Revolutions Per Minute.

Time.	Reference No.	Revolutions per minute.	Power Readings. Average current.	Power Readings. Average E. M. F.	Electrical horse power.	Horse power input.	Suction head.	Discharge Head. Pressure gage.	Discharge Head. Water gage No. 9.	Discharge Head. Mercury manometer	Total head.	Head on weir.	Discharge cubic feet per second.	Horse power output.	Efficiency.
		R. P. M.	Amp.	Vol's	E. H. P.	B. H. P.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		HP	%
May 17, '06 3:50.......	1	1,273	33.0	383.2	16.9	13.5	—5.6	26.0	....	25.9	31.5	.4860	1.68	6.0	44.6
4:00.......	2	1,275	27.1	384.4	13.9	10.5	—3.4	30.0	....	29.5	32.9	.3882	1.22	4.5	33.3
4:05.......	3	1,282	30.4	385.4	15.7	12.2	—3.7	27.7	....	28.7	32.4	.4450	1.49	5.5	45.0
4:10.......	4	1,279	27.2	381.6	14.0	10.6	—3.4	30.0	....	29.8	33.2	.4018	1.28	4.8	45.5
4:15.......	5	1,274	26.0	378.4	13.2	9.9	—3.3	30.5	....	30.3	33.6	.3857	1.21	4.6	46.7
4:20.......	6	1,273	21.8	413.0	12.1	8.5	—3.1	31.0	....	30.9	34.0	.3300	0.96	3.7	43.6
4:25.......	7	1,275	19.4	405.8	10.5	7.0	—2.8	32.0	....	32.0	34.8	.2942	0.81	3.2	45.7
4:30.......	8	1,283	16.5	411.6	9.1	5.6	—2.8	32.0	..	32.2	35.0	.2274	0.55	2.2	39.0
4:35.......	9	1,279	14.0	419.0	7.9	4.3	—2.7	31.0	....	31.6	34.3	.1798	0.39	1.5	35.4
4:40	10	1,289	12.2	401.8	6.0	3.2	—2.6	29.5	....	30.1	32.7	.1365	0.26	1.0	30.0
4:45.......	11	1,293	12.1	407.4	6.6	3.2	—2.6	29.5	....	30.2	32.8	.1204	0.22	0.8	25.6
†4:50-4:53.	12	1,285	9.5	379.4	4.8	1.7	2.6	26.5	....	26.2	28.8	.0000	0.00	0.0	00.0
4:55-5:00..	13	1,252	39.3	340.2	17.9	15.0	5.7	15.8	....	16.1	21.8	.5858	2.20	5.5	36.4
5:05.......	14	1,243	40.0	363.6	19.5	16.3	—6.0	5.0	....	5.0	11.6	.6087	2.33	3.1	18.8
5:13.......	15	1,259	42.1	353.0	19.9	16.8	—6.0	4.0	....	4.2	10.2	.6189	2.39	2.8	16.4
5:20.......	16	1,256	44.5	312.6	20.4	17.4	—6.2	3.5	....	4.3	10.5	.6191	2.39	2.9	16.4

TABLE VIII.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP ENTRANCE TO PUMP UNDER SUCTION

(Air leakage condition No. 1.)

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS-SECTION CIRCULAR, 3½" DIAMETER; THROAT OPEN 3½" DIAMETER. VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛" x 2⅛") IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,250 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head (inches of mercury.)	Suction head, water gage No. 0.	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT CENTER LINE OF DISCHARGE CHAMBER.								READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, ⅜ INCHES OUTSIDE OF INNER EDGE OF VORTEX.					MERCURY MANOMETER FOR GAGE NO. 5'		Reading of water gage No. a. for balance chamber.	Reading of water gage No. .
									Mercury manometer.																		
		Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9	Left.	Right.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 1.	No. 2.	No. .	No. 5.	No. 6.	Left.	Right.		
	RPM	Amp.	Volts	F.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	F.	Ft.	Ft.	Ft.
April 10, 1906						o		o				o	o	o	o	o	o		o	o	o	o	o			o	o
3:55— : 0....	1,232	.1	375.4	.08	5.5	—6.5	4.0	4.2	1.69	1.50	3.6	4.5	5.5	5.3	4.2	2.4	—2.0	3 2	—2.8	—5.4	—6.8	—12 3	—21.0	......	......	—2.6	—3.7
4:05—:10....	1,235	38.6	384.	.609	5.5	—6.5	4.0	4.3	1 69	1.49	.1	3.7	5.3	5.1	4.3	2.3	—2.0	3.0	—2.8	—6.3	—6.9	—12.8	—21.0	......	......	—2.7	—3.7
4:15—:2	1,234	40.4	395.0	.6105	5.4	—6.5	4.0	4.3	1.70	1.49	3.3	.9	5.4	5.3	4.4	2.3	—2.0	3.0	—2.8	—6.2	—7.5	—13.0	......	......	......	—2.6	—3.8
Averages..	1,234	39.0	385.0	.6096	5.5	—6.5	4.0	4.3	1.6	1.49	3.3	4.0	5.4	5.2	4.3	2.3	—2.0	3.1	—2.8	—6.0	—7.1	—12.7	—21.0	......	......	—2.6	—3.7
April 11, 190						o		c			c	c			c	c	c	c	c	c	c		o			o	o
3:55—:00....	1,252	38.0	362.1	.5632	4.5	—5.8	20.5	6.6	2.30	0.86	6.1	.4	6.5	5.8	5.0	3.3	0.0	5.5	.2	5.2	6.0	0.4	—2.4	1.67	1.40	—1.8	—3.1
4:15—4:20....	1,240	38.2	351.2	.5612	4.8	—5.9	21.0	6.0	2.28	0.86	5.4	5.8	5.	5.0	4 1	2.5	—1.0	4.9	6.9	4.7	5.5	0.0	—1.5	1.67	1.41	—1.8	—3.2
:30—4:35....	1,260	38.3	368.0	.5659	4.8	—5.8	21.0	7.2	2.31	0.83	6.8	7.1	7.2	6.3	5.4	3.6	+0.1	6.1	8.1	6.1	6.8	0.4	—1.9	1.65	1.41	—1.7	—3.2
4:5—:50....	1,263	39.0	374.1	.5652	4.8	—5.8	21 0	4.9	2.30	0.81	4.2	4.4	4.5	3.8	2.9	1.2	—2.6	3.7	8.0	6.1	6.8	0.0	—2.2	1.67	1.40	—1.6	—3.2
5:05—5:10....	1,249	35.9	390.3	.5626	4.5	—5.8	19.5	5.0	2 28	0.87	4.5	4.8	4.9	4.0	3.2	1.5	—1.6	3.9	6.5	3.9	5.0	0.0	—1.3	1.66	1.40	—1.8	—3.2
Averages..	1,253	37.9	369.1	.5636	4.7	—5.8	20.6	5.9	2.29	0.85	5.4	5.7	5.8	5.0	4.1	2.4	—1.0	4.8	7.3	5.2	6 0	0.2	—1.9	1.66	1.40	—1.7	—3.2

April 12, 190						o		c			c		c	c	c	c	c	c	c	c	c	c	c			o	
3:50—3:55....	1,245	17.8	428.3	.3052	2.2	—3.0	28.0	5.7	2.64	0.50	3.4	3.4	3.5	2.6	2.1	1.4	0.3	5.1	5.6	4.1	2.7	1.2	1.8	2.11	0.95	+0.7	—1.5
4:10—4:15....	1,259	17.8	426.2	.3052	2.5	—3.0	28.0	5.6	2.64	0.50	3.3	3.3	3.4	2.5	2.0	1.4	0.3	5.0	5.4	3.9	2.4	0.8	1.4	2.09	0.97	+0.7	—1.5
4: 0—4: 5....	1,230	17.6	418.8	.3020	2.5	—3.0	27.5	5.5	2.60	0.53	3.3	3.3	3.4	2.5	2.1	1.4	0.4	5.0	4.9	3.6	2.2	0.7	1.2	2.10	0.96	+0.7	—1.5
: 0— :35....	1,235	18.4	413.6	.3040	2.5	—3.0	28.0	5.6	2.61	0.55	3.5	3.5	3.6	2.7	2.2	1.5	0.4	5.0	5.4	3.9	2.3	0.9	1.5	2.10	0.96	+0.7	—1.5
4:45— :50....	1,252	17.6	446.0	.3060	2.5	—3.0	28.5	5.6	2.62	0.50	3.4	3.3	3.4	2.5	2.0	1.4	0.4	5.0	4.9	3.7	2.3	0.8	1.4	2.11	0.94	+0.7	—1.5
5:05—5:10....	1,249	17.0	480.8	.3085	2.5	—3.0	28.5	5.4	2.63	0.50	3.1	3.1	3.3	2.4	1.8	1.2	0.1	4.8	5.7	4.2	2.9	1.1	1.6	2.11	0.94	+0.7	—1.4
Averages..	1,245	17.7	435.6	.3052	2.4	—3.0	28.1	5.6	2 2	0.51	3.3	3.3	3.4	2.5	2.0	1.4	0.3	5.0	5.3	3.9	2.5	0.9	1.5	2.10	0.95	+0.7	—1.5
April 24, 1905						o		c			c	c		c	c	c	c	c	o	o	o	o	o				
2:27— :30....	1.261	37.3	351.7	.5564	4.4	—5.5	13.0	5.7	2.02	1.13	5.8	5.8	6.1	5.1	4.3	2.5	—0.7	4..	4.3	2.9	1.1	—4.1	—13.5	......	......	.....	.....
3:39— :42....	1.266	40.7	349.2	.5560	.....	......	.....	.....	......	......	....	....	....	....	....	....	.....	.....	.....	.....	.....	......	......	......	......	.....	.....
Averages..	1,264	39.0	350.4	.5562	4.4	—5.5	13.0	5.7	2.02	1.13	5.8	5.8	6.1	5.1	4.3	2.5	—0.7	4.7	4.3	2.9	1.1	—4.1	—13.5	......	......	.....	.....
April 24, 1906						o		c					c	c	c	c	c	c	o	o	o	o	o				
4:10— :13....	1.258	35.1	354.4	.5076	4.0	—5.0	13.5	5.5	2.05	1.10	5.0	5.4	5.4	4.3	3.3	1.7	—1.5	4.6	6.0	3.2	1.2	—1.5	—6.1	......	......	.....	.....
4:22—4:25....	1.240	36.3	338.4	.5060	4.0	—4.9	13.5	5.5	2.05	1.10	5.1	5.2	5.3	4.4	3.4	1.8	—1.4	4.4	6.0	3.0	1.4	—1.5	—6.2	......	......	.....	.....
4:32—4:35....	1 248	37.0	338.0	.5135	.....	......	.....	5.8	2.10	1.06	5.2	5.3	5.3	4.5	3.6	1.8	—1.4	4.8	7.0	4.0	2.7	—1.4	—6.2	......	......	.....	.....
4:42—4:45....	......	35.5	351.6	.5227	4.0	—5.1	14.2	5.8	2.11	1.05	5.5	5.5	5.4	4.7	3.6	2.0	—1.2	4.8	7.0	3.8	2.5	......	......	......	......	.....	.....
4:57—5:00....	1,237	36.6	327.6	.5188	4.0	—5.0	14.5	5.9	2.09	1.06	5.2	5.4	5.5	4.7	3.7	2.2	—1.0	4.9	7.0	3.8	2.5	......	......	......	......	.....	.....
Averages..	1,246	36.1	342.0	.5137	4.0	—5.0	13.9	5.7	2.08	1.07	5.2	5.4	5.4	4.5	3.5	1.9	—1.3	4.7	6.6	3.6	2.1	—1.5	—6.2	......	......	.....	.....
April 24, 190						o																					
+5:20—5:30...	1,234	8.1	431.6	.0000	2.2	—2.6	21.3	.....	2.33	.81	....	....	....	....	....	....	.....	.....	.....	.....	.....	......	......	......	......	.....	.....

TABLE

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX-INCH HORI-

Air leakage,

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS SECTION CIRCULAR 3½" DIAMETER; THROAT
VANES, RADIAL WITH ENTRANCE CURVED, AREA OF

SPEED OF PUMP, 1,250 REVOLUTIONS PER MINUTE.

TIME.	Reference number.	Revolutions per minute.	POWER READINGS.		Electrical horse-power.	Horse-power input.	Suction head (water gage No. 0)	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge cubic feet per second.	Horse-power output.
			Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer.				
		R. P. M.	Amp.	V lts	E. H.P.	B. H.P.	Ft.	F .	Ft.	Ft.	Ft	Ft.		H.P.
April 10, 1905. 3:55—4:20......	1	1,234	39.0	385.0	20.1	15.7	o —6.7	4.	o 4.3	4.2	10.7	. 0.06	2.33	2.8
April 11, 1905. 3:55—5:10......	2	1,2 3	37.9	369.1	18.8	15.6	o —5.8	20.6	c 5.9	20.4	2 .2	.56 6	2 09	6.2
April 12, 1906. 3:50—5:10......	3	1,245	17.7	435.6	10.3	6.6	—3.0	28.	c . .6	29.2	32.	. 052	0.8	3.1
April 24, 1906. 3:27—3: 2......	4	1,264	39.0	350.4	18.3	15.2	o —5.5	13.0	c 5.7	13.2	18.7	.5562	2.04	4.4
April 24, 1905. 4:10—5:00......	5	1,246	35.1	342.0	16.5	13.6	o —5.0	13.9	c 5.7	14.8	19.8	.5137	1.82	4.1
April 29, 1906. +5:20— :30.....		1,234	8.1	431.6	4.7	1.2	o —2.6	21.3		21.4	24.0	.0000	0.0	0.0

IX.

ZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION.

condition No. 1.

OPEN 3½" DIAMETER. VORTEX. RECTANGULAR IN CROSS SECTION (1⅝" x 2⅝") IMPELLER. 12
CROSS-SECTION OF WATER-WAY PRACTICALLY CONSTANT.

Efficiency.	HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER. Water Gages.								HYDRAULIC GRADIENT. ¾ INCHES OUTSIDE OF INNER EDGE OF VORTEX. Water Gages.						Mercury manometer for gage No. 5.	Balance chamber, pressure, gage No. a.	Pressure at gage No. b.
	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.			
%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
17.0	o 3.3	o 4.0	o 5.4	o 5.2	o 4.5	o 2.3	o 2.0	3.1	o −2.8	o −6.0	o −7.1	....	o −1..7	o −1.0	......	o −2.6	o −3.7
39.9	c 5.4 19.9	c 5.7 20.2	c 5.8 20.3	c 5.0 19.5	c 4.1 18.	c . 16.9	c −1 0 +13.5	c 4.8 19 3	c 7.5 10.6	c 5.2 8.5	c 6.0 9.3	....	c 0.2 3.5	o −1.9	...... +3.5	o −1.7	o − .2 .....
47.2	c 3.3 25.9	c 3. 25.9	c 3.4 27.0	c 2.5 26.1	c 2.0 25.6	c 1. 25.0	c 0.3 23..	c 5.0 28.6	c 5.3 29.0	c 3.9 18.6	c 2.5 17.2	....	c 0.9 15.	c 1.5 16.2	.... 15.6	o +0.	o 1.5 .....
28.6	c 5.8 13.3	c .8 13.3	c .1 13.6	c 5.1 12.6	c 4.3 11.9	c 2.5 10.0	c −0.7 +6.8	c 4.7 12.2	o 4.3	o 2.9	o 1.1	....	o −4.1	o −13 5	....	....	....
30.1	c 5.2 14.3	c 5.4 14.5	c 5.4 14.5	c 4.5 13.6	c 3.5 12.6	c 1.9 11.0	c −1.3 +7.8	c 4.7 13.8	o 6.6	o 3.6	o 2.1	....	o −1.5	o −6.2	....	....	....
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	....	.....	.....	.....	.....	.....

TABLE X.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER. FORM CIRCULAR. CROSS-SECTION CIRCULAR, 3½" DIAMETER. THROAT OPEN, 3½" DIAMETER. VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x2"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED. AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP; 1120 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head. (Pressure.)	DISCHARGE HEAD.			READING OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.								Reading of water gage No. a. for balance chamber.
		Average current.	Average E. M. F.			Water gage No. 9.	Mercury manometer. Left.	Mercury manometer. Right.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
	R.P.M.	Amps.	Volts.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
April 8, 1908					o	c			c	c	c	c	c	c	c		o
11:50—11:55	1,125	28.8	471.0	6,290	1.3	1.8	3.95	2.99	3.2	4.3	5.5	5.8	4.8	2.7	—1.8	1.4	4.2
12:35—11:45	1,120	27.5	471.9	6,270	1.0	....	3.95	2.99									
Averages	1,122	28.2	471.4	6,280	1.2	1.8	3.95	2.99	2.1	4.3	5.5	5.8	4.8	2.7	—1.8	1.4	4.2
April 8, 1908.					o												o
12:00—12:05	1,126	27.1	475.2	5,900	1.7	....	4.15	2.76	......	......	......	......	......	......	......	......	5.1
April 8, 1908					o												o
12:18—12:23	1,130	24.1	471.9	5,070	2.8	....	4.36	2.51	......	......	......	......	......	......	......	......	6.2
12:25—12:30	1,122	23.8	473.0	5,050	2.8	....	4.35	2.52	......	......	......	......	......	......	......	......	6.2
Averages	1,126	23.9	472.4	5,060	2.8	....	4.35	2.52	......	......	......	......	......	......	......	......	6.2
April 8, 1908.					o												o
3:05—3:15	1,117	26.0	457.0	5,540	2.4	....	4.26	2.64	......	......	......	......	......	......	......	......	6.0

April 8, 1908.					o												o
3:25—3:30	1,121	21.5	469.9	4,420	3.5	....	4.51	2.35	......	......	......	......	......	......	......	......	6.8
3:40—3:50	1,121	21.5	469.4	4,390	3.5	....	4.49	2.37	......	......	......	......	......	......	......	......	6.8
Averages	1,121	21.5	469.7	4,400	3.5	....	4.50	2.36									6.8
April 8, 1908.					o												o
4:00—4:05	1,120	18.8	463.8	3,710	4.0	....	4.59	2.26	......	......	......	......	......	......	......	......	7.4
April 8, 1908.					o												o
4:10—4:20	1,126	16.5	466.0	3,040	4.3	....	4.60	2.24	......	......	......	......	......	......	......	......	7.8
April 8, 1908.				0,000	o												
4:23—4:27	1,131	9.4	473.1	....	5.3	....	4.40	2.47									

TABLE XI.

SUMMARY SHEET; RESULTS OF EXPERIMENTS ON SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS-SECTION CIRCULA , 3½" DIAMETER; THROAT OPEN, 3½" DIAMETER. VORTEX RECTANGULAR IN CROSS-SECTION. (1¼" x 2"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVE , AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP: 1120 REVOLUTIONS PER MINUTE.

TIME.	Reference No.	Revolutions per minute.	POWER READINGS.		Electrical horse power	Horse power input.	Suction head. (Pressure).	DISCHARGE HEAD.		Total head.	Head on weir.	Discharge, cubic feet per second.	Horse power output.	Efficiency.	HYDRAULIC GRADIENT: CENTER LINE OF DISCHARGE CHAMBER.								Balance chamber Pressure gage No. A.
															Water gages.								
			Average current.	Average E. M. F.				Water gage No. 9.	Mercury manometer.						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
		R.P.M	Amps.	Volts	E.H.P	B.H.P	Ft.	Ft.	Ft.	Ft.	Ft.	Cu.ft	H. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
April 8, 1908 11:50 12:45	1	1122	28.2	471.4	17.6	13.7	o 1.2	c 1.8	16.0	14.8	6280	2.44	4.09	.9.9	c 3.2 17.4	c 4.3 18.5	c 5.5 19.7	c 5.8 20.0	c 4.8 19.0	c 2.7 16.9	c -1.8 12.4	1.4 15.6	o 4.2
April 8, 19 8 12:00—12:05	2	1126	27.1	475.2	17.3	13.4	o 1.7	......	21.7	20.0	5900	2.23	5.06	37.8	......	......	......	......	......	......	......	......	o 5.1
April 8, 1908 12:18–12:3	3	1126	23.9	472.4	15.1	11.1	o 2.8	......	27.4	24.6	5060	1.78	4.98	48.6	......	......	......	......	......	......	......	......	o 6.2
April 8, 1908 3:05 – 3: 5	4	1117	26.0	4 7.0	15.9	11.9	o 2.4	......	24.7	22.3	5540	2.03	5.14	43.2	......	......	......	......	......	......	......	......	o 6.0
April 8, 1908 3:25 — 3:50	5	1121	21.5	469.7	13.5	9.4	o 3.5	......	31.5	28.0	4100	1.46	4.64	49.1	......	......	......	......	......	......	......	......	o 6.8
April 8, 1908 4:00 — 4:05	6	1120	18.8	463.8	11 7	7.6	o 4.0	......	34.0	30.0	3710	1.14	3 90	51.4	......	......	......	......	......	......	......	......	o 7.4
April 8, 19 8 4:10 — 4:20	7	1126	16.5	466.0	10.3	6.1	o 4.3	......	34.3	30.0	3040	0.85	2.9	47.5	......	......	......	......	......	......	......	......	o 7.8
April 8, 1908 †4:2 — 4:27	8	1131	9.4	473.1	5.9	1.5	o 5.3	......	28.7	23.4	0000	0.00	0	0.0	......	......	......	......	......	......	......	......	—

TABLE XII.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS-SECTION CIRCULAR, 3½" DIAMETER; THROAT OPEN, 3½" DIAMETER. VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x2"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED; AREA OF CROSS-SECTION AT WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1300 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head. (Pressure.)	DISCHARGE HEAD.		Reading of water gage No. a, for balance chamber.
		Average current.	Average E. M. F.			Mercury manometer.		
						Left.	Right.	
	R.P.M.	Amps.	Volts.	Ft.	Ft.	Ft.	Ft.	Ft.
April 8, 1908. 5:10—5:15................	1.304	36.9	481.6	6.735	o 1.0	4.03	2.90	o 5.0
April 8, 1908. 5:20—5:30................	1.303	36.5	481.5	6.410	o 1.5	4.34	2.55	o 5.9
April 8, 1908. 9:10—9:20................	1.297	36.7	463.2	5.840	o 2.1	4.52	2.33	o 6.5
April 8, 1908. 9:23—9:33................	1.298	31.2	462.4	5.230	2.8	4.70	2.13	o 7.4
April 8, 1908. 9:37—9:50................	1.302	27.5	470.4	4.610	o 3.5	4.90	1.91	o 8.3
April 9, 1908. 9:55—10:08...............	1.303	28.5	453.8	4.605	3.5	4.90	1.91	o 8.3
Averages..........	1.302	28.0	461.6	4.607	3.5	4.90	1.91	o 8.3
April 9, 1908. 10:10—10:30..............	1.302	23.9	465.0	3.890	o 4.1	4.98	1.83	o 8.8
April 9, 1908. 10:30—10:38.............	1.302	1 .2	453.0	2.965	o 4.5	4.98	1.83	o 9.0
April 9, 1908. *10:40—10:50............	1.306	9.5	456.4	0.0	o 5.4	4.67	2.17	—

TABLE XIII.

SUMMARY SHEET: RESULTS OF EXPERIMENTS ON SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER, FORM CIRCULAR, CROSS-SECTION CIRCULAR, 3½" DIAMETER; THROAT OPEN, 3½" DIAMETER. VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛" x 2"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATER WAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1,300 REVOLUTIONS PER MINUTE.

TIME.	Reference No.	Revolutions per minute.	POWER READINGS.		Electrical horse power.	Horse power input.	Suction head. (Pressure).	Dis. head.	Total head.	Head on weir.	Discharge cubic feet per second.	Horse power output.	Efficiency.	Balance chamber Pressure gage No. a.
			Average current.	Average E. M. F.				Mercury manometer						
		RPM	Am's	Volts	EHP	BHP	Ft.	Ft.	Ft.	Ft.	Cu. Ft.	H.P.	%	Ft.
April 8, 1908. 5:10—5:15......	1	1,304	36.9	481.6	23.8	19.6	1.0	18.2	17.2	6,735	2.71	5.30	27.0	$\overset{o}{5.0}$
April 8, 1908. 5:20—5:30......	2	1,303	36.5	481.5	23.7	19.5	$\overset{o}{1.5}$	26.9	25.4	6,410	2.52	7.29	37.4	$\overset{o}{5.9}$
April 8, 1908. 9:10—9:20......	3	1,297	36.7	463.2	21.6	17.5	$\overset{o}{2.1}$	32.1	30.0	5,840	2.19	7.46	42.6	$\overset{o}{6.5}$
April 8, 1908. 9:23—9:33......	4	1,298	31.2	462.4	19.5	15.4	$\overset{o}{2.8}$	35.0	34.2	5,230	1.87	7.29	47.1	$\overset{o}{7.4}$
April 8, 1908. 9:37—10:08.....	5	1,302	28.0	461.6	17.3	13.2	$\overset{o}{3.5}$	42.8	39.3	4,607	1.56	6.96	52.6	8.3
April 9, 1908. 10:10—10:30....	6	1,302	23.9	465.0	14.9	10.8	$\overset{o}{4.1}$	44.6	40.5	3,890	1.23	5.67	52.6	$\overset{o}{8.8}$
April 9, 1908. 10:30—10:38....	7	1,302	19.2	453.0	11.7	7.1	$\overset{o}{4.5}$	44.6	40.1	2,965	0.82	3.74	49.2	$\overset{o}{9.0}$
April 9, 1908. †10:40—10:50...	8	1,306	9.5	456.4	5.8	1.4	$\overset{o}{5.4}$	36.1	30.7	0000	0.00	0.00	0.0	.....

TABLE XIV.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION. (Slight air leakage; condition No. 2.)

DISCHARGE CHAMBER. FORM SPIRAL, CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED ($1\frac{1}{8}''\times\frac{1}{2}''$); VORTEX, RECTANGULAR IN CROSS-SECTION ($1\frac{1}{8}''\times2\frac{1}{2}$). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1120 REVOLUTIONS PER MINUTE.

Time.	Average revolutions of pump per minute.	Field current. (Amperes.)	Power Readings.		Average head on weir.	Suction head. (Inches of mercury.)	Discharge Head.				Readings of Water Gages for Hydraulic Gradient. Center Line of Discharge Chamber.							
			Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer.		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
									Left.	Right.								
	R.P.M.		Amp.	Volts.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
July 25, 1906.								o			o							
3: 5- 3:31...	1121	0.35	30.9	407.7	.62 5	6.2	5.0	5.1	[1]2.00	1.64	5.0	0.6	1.1	2.2	3.5	4.5	5.3	5.0
3:40- 3:45...	1130	0.35	30.5	402.1	.6285	6.2	5.0	5.2	2.00	1.64	4.9	0.4	0.8	2.1	3.5	4.5	5.3	5.0
4:05- 4:10...	1121	0.35	30.0	399.7	.6292	5.9	4.5	4.9	1.99	1.64	4.4	0.0	0.5	1.7	3.3	4.1	5.0	4.7
4:15- 4:20...	1118	0.37	28.1	437.5	.6178	5.7	4.5	4.9	1.93	1.70	4.4	—0.1	0.4	1.9	3.2	4.2	5.0	4.8
4:30- 4:35...	1142	0.36	27.9	438.4	.6191	5.7	4.8	4.9	1.93	1.70	4.4	0.0	0.5	1.7	3.2	4.1	5.0	4.7
4:40- 4:45...	1141	0.37	28.3	424.5	.6185	5.7	4.5	4.9	1.93	1.70	4.5	0.1	0.5	1.7	3.2	4.1	5.0	4.8
4:57- 5:02...	1129	0.37	27.8	428.0	.6180	5.7	4.7	4.9	1.93	1.70	......	......	......	......	......	......	......	......
Averages..	1129	0.36	29.1	419.7	.6229	5.9	4.7	5.0	1.96	1.67	4.6	0.2	0.6	1.9	3.3	4.2	5.1	4.8
July 26, 1906.								c			c							
†9:45- 9:50...	1151	0.40	7.65	469.8	.0000	2.2	22.4	5.0	[1]2.56	1.02	2.2	3.2	4.2	4.6	4.8	4.9	4.9	4.9
†9:58-10:08...	1131	0.39	7.57	462.1	.0000	2.3	22.0	5.3	2.57	1.02	2.7	3.6	4.5	4.9	5.1	5.2	5.2	5.3
†10:15-10:20...	1148	0.40	7.55	464.6	.0000	2.3	22.3	4.9	2.57	1.01	2.2	3.1	4.1	4.5	4.7	4.8	4.8	4.9
†10:37-10:4[illegible]...	1106	0.40	7.22	454.6	.0000	2.3	21.0	4.9	2.53	1.05	2.1	3.1	4.0	4.4	4.6	4.7	4.7	4.9
†10:55-11:00...	1145	0.40	7.18	487.4	.0000	2.3	22.5	4.9	2.59	.99	2.0	3.1	4.0	4.5	4.7	4.8	4.9	4.9
Averages..	1136	0.40	7.43	467.7	.0000	2.3	22.0	5.0	2.56	1.02	2.2	3.2	4.2	4.6	4.8	4.9	4.9	5.0
July 26, 1906.								c			c							
11:16-11:25...	1142	0.39	9.0	463.8	.1197	2.4	24.7	5.5	[1]2.68	.90	0.3	1.7	3.5	4.5	5.0	5.2	5.4	5.5
11:33-11:40...	1135	0.40	9.2	462.7	.1195	2.4	25.2	5.6	2.67	.90	0.2	1.7	3.6	4.5	5.0	5.3	5.5	5.6
11:45-11:55...	1138	0.39	8.9	468.7	.1200	2.4	25.5	5.6	2.69	.89	0.3	1.7	3.5	4.5	4.9	5.2	5.4	5.6
Averages..	1138	0.39	9.0	465.1	.1197	2.4	25.1	5.6	2.68	.90	0.3	1.7	3.5	4.5	5.0	5.2	5.4	5.6

[1] 0.1 ft. of water on left column of mercury manometer all day.

TABLE XIV—Continued.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

Time.	Average revolutions of pump, per minute.	Field current. (Amperes.)	Power Readings.		Average head on weir.	Suction head. (inches of mercury.)	Discharge Head.				Readings of Water Gages for Hydraulic Gradient. Center Line of Discharge Chamber.							
			Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer. Left.	Mercury manometer. Right.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
	R.P.M.		Amp.	Volts.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	1 t.	Ft.	Ft.	Ft.	Ft.	Ft.
July 27, 1906.								c			c							
4:25- 4:30...	1123	0.35	29.2	408.6	.6160	5.9	9.5	5.3	^{1}2.11	1.50	4.9	5.2	1.3	2.3	3.8	4.6	5.6	5.2
4:40- 4:47...	1145	0.35	29.3	416.7	.6152	5.9	10.0	5.3	2.12	1.50	4.3	5.2	0.9	2.1	3.5	4.5	5.4	5.1
Averages..	1136	0.35	29.2	412.6	.6156	5.9	9.8	5.3	2.12	1.50	4.6	5.2	1.1	2.2	3.6	4.6	5.5	5.2
July 28, 1906.								c			c							
9:55-10:00..	123	0.35	27.1	403.6	.5937	5.4	11.0	5.9	^{1}2.18	1.43	4.0	5.0	1.3	2.7	4.2	5.1	6.0	5.8
10:10-10:17...	1116	0.33	27.6	394.0	.5965	5.4	9.5	5.8	2.12	1.49	4.1	5.0	1.5	2.6	4.1	5.0	5.8	5.7
10:25-10:35...	1110	0.34	27.5	398.9	.5955	5.4	9.5	5.7	2.12	1.50	4.2	5.1	1.6	2.6	4.1	5.0	5.8	5.6
10:40-10:50...	1109	0.33	28.4	376.6	.5972	5.4	9.7	5.8	2.11	1.51	4.4	5.4	1.8	2.8	4.3	5.2	5.9	5.7
Averages.	1114	0.34	27.6	393.3	.5957	.4	9.9	5.8	2.13	1.48	4.2	5.1	1.6	2.7	4.2	5.1	5.9	5.7
July 28, 1906.								c			c							
11:00-11:.0...	1125	0.35	27.4	410.7	.5820	5.1	15.5	5.5	^{1}2.34	1.26	2 2	4.0	0.7	2.1	3.5	4.5	5.4	5.3
11:15-11:20...	1144	0.38	26.2	428.8	.5822	5.0	15.2	5.5	2.32	1.28	2.4	4.0	0.7	2.1	3.6	4.6	5.5	5.3
11:30-11:36...	1152	0.36	27.2	421.9	.5830	5.1	15.5	5.5	2.34	1.26	2.3	4.1	0.7	2.1	3.7	4.6	5.5	5.3
11:45-11:52...	1138	0.35	6.2	418.1	.5805	5.2	15.5	5.5	2.34	1.27	2.2	4.0	0.7	2.1	3.7	4.7	5.6	5.4
12:00-12:06...	1138	0.37	27.1	429.5	.5840	5.2	15.5	5.5	2.35	1.26	2.2	3.9	0.5	2.0	3.6	4.5	5.5	5.4
Averages.	1139	0.36	26.8	421.8	58.23	5.1	15.4	5.5	2.34	1.27	2.3	4.0	0.7	2.1	3.6	4.6	5.5	5.3
July 30, 1906.								c			c							
10:30-10:35...	1128	0.35	27.6	4 0.2	.5964	5.4	16.0	5.6	^{1}2.36	1.24	2.7	3.1	0.9	2.3	3.8	4.7	5.7	5.5
10:48-10:55...	1122	0.35	26.7	400.7	.5933	5.4	16.2	5.5	2.36	1.24	2.8	3.1	0.9	2.3	3.7	4.6	5.6	5.4
11:00-11:10...	1123	0.35	27.9	408.2	.5998	5.4	15.8	5.6	2.36	1.23	2.8	3.3	1.0	2.4	3.8	4.8	5.7	5.5
11:15-11:20...	1119	0.36	26.9	399.3	.5940	5.3	15.8	5.5	2.34	1.26	2.7	3.2	1.1	2.4	3.6	4.0	5.5	5.4
11:30-1 :35...	1109	0.34	27.6	402.2	.5922	5.4	16.0	5.5	2.35	1.25	2.8	3.2	0.9	2.3	3.8	4.6	5.5	5.4
11:42-11:50...	1113	0.35	26.8	411.4	.5938	5.3	16.2	5.6	2.36	1.24	2.7	3.2	0.9	2.3	3.8	4.7	5.7	5.5
1.:55-12:00...	1119	0.36	26.8	410.7	.5946	5.4	6.2	5.6	2.36	1.24	2.7	3.1	0.9	2.2	3.7	4.7	5.6	5.5
Averages.	1119	0.35	27 .2	404.7	.5949	5.4	16.0	5.6	2.36	1.24	2.7	3.2	0.9	2.3	3.7	4.7	5.6	5.5

July 30, 1906.								c			c							
12:07 12: 8...	1129	0.35	25.6	407.4	.5652	4.9	20.2	5.6	[1]2.50	1.09	0.9	2.4	0.5	2.1	3.6	4.5	5.4	5.5
12:23-12:28...	1130	....	25.5	418.4	.5688	4.9	20.0	5.5	2.50	1.10	0.9	2.3	0.5	2.0	3.4	4.4	5.3	5.4
Averages.	1130	0.35	25.6	412.9	.5670	4.9	20.1	5.6	2.50	1.10	0.9	2.4	0.5	2.0	3.5	4.4	5.4	5.4
August 1, 1906.								c			c							
3: 5 4:00...	1134	0.36	26.4	420.9	.5720	5.2	20.0	5.5	[1]2.49	1.11	1.0	2.3	0.5	2.0	3.6	4.5	5.5	5.5
4:10 4:15...	1144	0.35	26.6	427.3	.5745	5.1	20.0	5.5	2.50	1.09	1.1	2.3	0.5	2.1	3.5	4.6	5.5	5.5
4:25 4:30...	1140	0.36	26.7	415.1	.5740	5.2	20.5	5.5	2.50	1.08	0.9	2.3	0.4	2.0	3.5	4.5	5.5	5.5
4:40 4:45...	1146	0.38	26.3	449.6	.5775	5.2	20.5	5.5	2.51	1.08	0.9	2.2	0.3	1.8	3.4	4.4	5.5	5.5
4:55 5:00...	1140	0.37	26.7	419.5	.5725	5.2	20.5	5.5	2.52	1.08	0.9	2.2	0.3	2.0	3.5	4.5	5.5	5.5
5:10 5:17...	1149	0.39	25.9	438.5	.5740	5.2	20.5	5.5	2.51	1.08	0.9	2.4	0.4	2.0	3.5	4.5	5.5	5.5
Averages.	1142	0.37	26.4	428.5	.5741	5.2	20.3	5.5	2.50	1.09	0.9	2.3	0.4	2.0	3.5	4.5	5.5	5.5
August 2, 1906.																		
11:40-11:50...	1154	....	18.6	419.1	.3760	3.1	27.5	....	[1]2.78	0.80	....	....	....	....	....	....	....	....
11:55-12:00...	1155	0.38	17.6	436.5	.3767	2.9	28.0	....	2.79	0.79	....	....	....	....	....	....	....	....
Averages.	1154	0.38	18.1	427.8	.3764	3.0	27.8	....	2.78	0.80	....	....	....	....	....	....	....	....
August 2, 1906.																		
12:12 12:18...	1140	....	26.7	426.1	.5825	5.2	20.0	....	[1]2.49	1.11	....	....	....	....	....	....	....	....
12:26-12:32...	1153	....	26.2	428.0	.5855	5.2	19.9	c	2.48	1.12	c	....	....	....	....	....	....	....
3:50- 4:00...	1130	0.33	26.9	409.7	.5768	5.1	20.0	5.5	2.49	1.10	1.2	1.8	0.5	2.0	3.5	4.5	5.5	5.5
4:05 4:15...	1128	0.33	26.5	390.6	.5750	5.2	20.0	5.5	2.50	1.09	1.1	2.0	0.4	2.0	3.5	4.5	5.5	5.5
4:20- 4:25...	1134	0.34	26.5	410.6	.5720	5.1	20.5	5.5	2.49	1.10	1.1	2.0	.5	2.0	3.5	4.5	5.5	5.6
Averages.	1137	0.33	26.6	413.0	.5784	5.2	20.1	5.5	2.49	1.10	1.1	1.9	0.5	2.0	3.5	4.5	5.5	5.5
August 2, 1906.								c			c							
4:20 4:3 ...	1138	0.36	24.1	413.7	.5120	4.4	24.3	6.5	[1]2.66	0.92	-0.1	1.9	1.1	2.8	4.3	5.4	6.4	6.5
4:45- 4:52...	1142	0.35	24.2	412.6	.5140	4.2	24.5	6.5	2.63	0.95	-0.1	1.9	1.1	2.8	4.3	5.4	6.4	6.5
5:00- 5:1 ...	1142	....	24.1	417.7	.5130	4.4	24.3	6.5	2.64	0.95	-0.2	1.9	1.0	2.7	4.3	5.4	6.3	6.5
Averages.	1141	0.36	24.1	414.7	.5130	4.3	24.4	6.5	2.64	0.94	-0.1	1.9	1.1	2.8	4.3	5.4	6.4	6.5
August 2, 1906.																		
5:22- 5:30...	1152	0.37	18.4	428.2	.3891	3.2	27.5	....	[1]2.77	0.80	....	....	....	....	....	....	....	....

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[1] 0.15 ft. of water on left column of mercury manometer all day.

TABLE XV.

SUMMARY SHEET; RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION (Slight air leakage; condition No. 2).

DISCHARGE CHAMBER, FORM SPIRAL. CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED (1⅛"x¼"). VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x2⅛"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED. AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1,120 REVOLUTIONS PER MINUTE.

Time.	Reference No.	Revolutions per minute.	Field current.	Power Readings.		Electrical horse power.	Horse power input.	Suction head.	Discharge Head.			Total head.	Head on weir.	Discharge cubic feet per second.	Horse power output.	Efficiency.	Hydraulic Gradient. Center Line of Discharge Chamber.							
																	Water gages.							
				Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer.						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
		R.P.M	Amp.	Amp.	Volts.	E.H.P	B.H.P	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		H. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
July 25, 1906. 3:25—5:02......	1	1,129	0.35	29.1	419.7	16.4	13.2	–6.7	4.7	o 5.0	5.7	11.7	.6229	2.41	3.2	24.3	o 4.6	0.2	0.6	1.9	3.3	4.2	5.1	4.8
July 26, 1906. †9:45—11:00.....	2	1,136	0.40	7.4	467.7	4.7	1.0	—2.6	22.0	c 5.0	22.0	24.6	.0000	0.00	0.0	0.00	c 2.2 19.2	3.2 20.2	4.2 21.2	4.6 1.6	4.8 21.8	4.9 21.9	4.9 21.9	5.0 22.0
July 26, 1906. 11:16—11:55....	3	1,138	0.39	9.0	465.1	5.6	2.0	—2.7	25.1	c 5.6	25.2	21.9	.1197	0.22	.7	35.0	c 0.3 19.9	1.7 21.3	3.5 23.1	4.5 24.1	5.0 24.6	5.2 24.8	5.4 25.0	5.6 25.2
July 27, 1906. 4:25—4:27.......	4	1,136	0.35	29.2	412.6	16.1	13.0	–6.7	9.8	c 5.3	10.1	16.8	.6156	2.36	4.5	34.1	c 4.6 9.4	5.2 10.0	1.1 5.9	2.2 7.0	3.6 8.4	4.6 9.4	5.5 10.3	5.2 10.0
July 28, 1906. 9:55—10:50......	5	1,114	0.34	27.6	393.3	14.6	11.7	—6.2	9.9	c 5.8	10.5	16.7	.5957	2.26	4.3	36.6	c 4.2 8.9	5.1 9.8	1.6 6.2	2.7 7.4	4.2 8.9	5.1 9.8	5.9 10.6	5.7 10.4
July 28, 1906. 11;00—12:06.....	6	1,139	0.36	26.8	421.8	15.1	11.8	—5.8	15.4	c 5.5	16.0	21.8	.5823	2.20	5.5	46.2	c 2.3 12.8	4.0 14.5	0.7 11.2	2.1 12.6	3.6 14.1	4.6 15.1	5.5 16.0	5.3 15.8

July 30, 1906. 10:30—12:00, ...	7	1,119	0.35	27.2	404.7	16.0	13.0	—6.2	16.0	[c] 5.6	16.6	22.8	.5919	2.26	5.9	45.0	[c] 2.7 13.7	3.2 14.2	0.9 11.9	2.3 13.3	3.7 14.7	4.7 15.7	5.6 16.6	5.5 16.5
July 30, 1906. 12:07—12:28.....	8	1,130	0.35	25.6	412.9	14.1	11.0	—5.6	20.1	[c] 5.6	20.3	25.9	.5670	2.12	6.2	56.0	[c] 0.9 15.6	2.4 17.1	0.5 15.2	2.0 16.7	3.5 18.2	4.4 19.1	5.4 20.1	5.4 20.1
Aug. 1, 1906. 3:55—5:17.......	9	1,142	0.37	26.4	428.5	15.2	11.8	—5.9	20.3	[c] 5.5	20.4	26.3	.5741	2.15	6.4	54.5	[c] 0.9 15.8	2.3 17.2	0.4 15.3	2.0 16.9	3.5 18.4	4.5 19.4	5.5 20.4	5.5 20.4
Aug. 2. 1906. 11:40—12:00.....	10	1,154	0.38	18.1	427.8	10.4	7.1	—3.4	27.8	.....	27.9	31.3	.3764	1.16	4.1	58.1	......	.....	.....	.....	.....	.....	.....	.....
Aug. 2, 1906. 12:12—4:25......	11	1,137	0.33	26.6	413.0	14.7	11.5	—5.9	20.1	[c] 5.5	20.2	26.1	.5784	2.17	6.4	56.0	[c] 1.1 15.8	1.9 16.6	0.5 15.2	2.0 16.7	3.5 18.2	4.5 19.2	5.5 20.2	5.5 20.2
Aug. 2. 1906. 4:30—5:10.......	12	1,141	0.36	24.1	414.7	13.7	10.5	—4.9	24.4	[c] 6.5	24.2	29.1	.5130	1.83	6.1	57.6	[c] -0.1 17.6	1.9 19.6	1.1 18.8	2.8 20.5	4.3 22.0	5.4 23.1	6.4 24.1	6.5 24.2
Aug. 2. 1906. 5:22—5:30.......	13	1,152	0.37	18.4	428.2	10.6	7.2	—3.7	27.5	.....	27.7	31.4	.3891	1.22	4.4	60.5	......	.....	.....	.....	.....	.....	.....	.....

TABLE XVI.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION.

(Slight air leakage. condition No. 2.)

DISCHARGE CHAMBER, FORM SPIRAL, CROSS-SECTION CIRCULAR, THROAT NEARLY CLOSED (1⅛"x½") VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x2⅛"). IMPELLER. 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP: 1290 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	Field current. (Amperes.)	POWER READINGS.		Average head on weir.	Suction head. (Inches of mercury.)	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT CENTER LINE OF DISCHARGE CHAMBER.							
			Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer.		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
									Left.	Right.								
	R.P.M.	Amp.	Volts.	E.M.F.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
August 3, 1906								c			c							
10:35-10:40...	1,293	0.31	41.3	396.4	.6415	6.3	10.5	6.5	[1]2.15	1.45	4.6	1.0	0.5	1.3	3.5	5.0	6.4	6.4
10:50-11:00...	1,297	0.30	41.7	398.3	.6420	6.3	10.8	6.5	2.16	1.46	4.5	1.1	0.4	1.4	3.5	5.0	6.4	6.4
11:10-11:15...	1,298	0.30	41.4	396.4	.6420	6.3	10.8	6.5	2.16	1.46	4.7	1.3	0.4	1.2	3.6	5.0	6.4	6.4
12:00-12:07...	1,302	0.32	38.1	435.8	.6430	6.3	11.0	6.5	2.16	1.45	4.6	1.9	0.3	1.4	3.6	5.0	6.5	6.4
August 4, ,06.																		
9:00-9:10.....	1,308	0.27	45.1	370.9	.6410	6.2	10.8	6.5	2.16	1.45	4.4	3.1	0.4	1.4	3.8	5.0	6.4	6.4
Averages....	1,300	0.30	41 5	399.6	.6419	6.3	10.8	6.5	2.16	1.45	4.6	.7	0.4	1.3	3.6	5 0	6 4	6.4
August 4, 1906.								c			c							
10:30-10:33...	1,305	0.30	41.5	390.7	.6400	6.3	15.7	6.5	[1]2.34	1.26	3.5	2.5	0.2	2.0	4.0	5.2	6.5	6.4
10:40-10:45...	1,296	0.30	43.1	376.9	.6370	6.3	15.5	6.5	2.33	1.27	3.2	2.4	0.2	2.1	4.0	5.2	6.5	6.4
11:15-11:20...	1,261	0.31	37.6	400 8	.6335	6.2	15.5	6.5	2.34	1.26	3.3	2.5	0.2	2.1	4.1	5.2	6.5	6.4
11:33-12:00...	1,286	0.30	42.8	373.1	.6340	6 2	15.5	6.5	2. 4	1.26	3.0	2.1	0.0	2.1	4.0	5.2	6.5	6.4
3:10-3:17.....	1,273	0.32	38.3	406.0	.6360	6.2	16.0	6.5	2.36	1.24	3.2	2.4	0.3	2.2	4.2	5.3	6.5	6.4
Averages....	1,284	0.31	40.7	391.1	.6361	6.2	15.6	6.5	2.36	1.26	3.2	2.4	0.2	2.1	4.1	5.2	6.5	6.4
August 4, 1906.								c			c							
3:30-3:34.....	1,272	0 35	35.8	440 9	.6220	5.9	20.5	6.5	[1]2.52	1.08	1.9	2.1	0.1	2.0	4.0	5.2	6.5	6.4
3:45-3:50.....	1,269	0.32	36.8	41 .5	.6230	5.9	20.5	6.5	2.51	1.08	1.9	2.0	0.1	2.0	3.9	5.2	6.4	6.4
4:20-4:25.....	1,280	0.36	34.4	443.9	.6225	5.8	20.5	6.5	2.51	1.08	2.1	2.2	0.1	2.0	4.0	5.2	6.4	6.4
Averages....	1,274	0.34	35.7	432.1	.6225	5.9	20. ,	6 5	2.51	1.08	2.0	2.1	0.1	2.0	4.0	5.2	6.4	6.4

August 4, 1906.								c			c							
4:28-4:33.....	1,273	0.36	33.5	435.5	.6000	5.4	25.0	6.5	[1]2.67	0.91	0.3	1.8	0.1	2.0	4.0	5.2	6.4	6.4
4:40-4:45. ...	1,285	0.35	33.3	446.3	.6005	5.4	25.0	6.5	2.68	0.90	0.1	1.5	-0.1	1.9	3.8	5.2	6.4	6.5
4:55-5:05.....	1.267	0.37	31.2	440.8	.5965	5.4	24.5	6.5	2.66	0.93	0.2	1.5	-0.2	2.0	4.0	5.2	6.4	6.5
5:10-5:25.....	1,261	0.35	32.1	440.6	.5965	5.4	25.0-	6.5	2.68	0.90	0.2	1.5	-0.2	2.0	3.9	5.2	6.4	6.4
Averages....	1.272	0.36	32.5	440.8	.5984	5.4	24.9	6.5	2.67	0.91	0.2	1.6	-0.1	2.0	3.9	5.2	6.4	6.4
August 4, 1906.																		
5:30-5:35.....	1.266	0.38	27.6	472.4	.5355	4.7	29.5	....	[1]2.84	0.76								
August 6, 1906.								c			c							
10:30-10:40...	1.288	0.30	36.7	376.3	.5497	4.6	29.5	6.5	[2]2.85	0.71	-1.8	1.9	-0.3	1.8	3.8	5.0	5.9	6.4
10:55-11:05...	1.291	0.30	35.0	402.0	.5522	4.7	30.0	6.5	2.87	0.68	-2.0	0.9	-0.5	1.7	3.7	5.1	6.2	6.4
11:20-11:30...	1.264	0.31	33.9	401.6	.5490	4.7	29.5	6.5	2.84	0.72	-1.9	1.0	-0.4	1.8	3.9	5.2	6.3	6.5
11:40-11:50...	1,283	0.30	36.4	382.4	.5520	4.9	30.3	6.5	2.87	0.69	-2.2	0.8	-0.7	1.6	3.6	5.0	6.2	6.4
12:00-12:10...	1.298	0.30	35.8	405.4	.5560	4.9	31.0	6.5	2.90	0.66	-2.3	0.7	0.8	1.6	3.6	5.0	6.2	6.4
Averages....	1.285	0.30	35.6	393.7	.5518	4.8	30.1	6.5	2.87	0.69	-2.0	0.9	-0.5	1.7	3.7	5.1	6.2	6.2
August 6, 1906.								c			c							
12:16-12:21...	1,293	0.32	27.1	426.4	.4508	3.6	34.8	6.5	[2]3.00	0.53	-3.7	0.0	0.0	1.8	3.8	5.0	6.0	6.4
3:30- 3:40...	1.297	0.32	27.2	417.1	.4525	3.6	34.2	6.5	2.99	0.55	-3.7	0.2	-0.2	1.8	3.8	5.1	6.0	6.5
3:52- 4:00 ..	1.296	0.30	26.4	426.0	.4530	.6	34.1	6.5	3.00	0.53	-3.4	.0	0.0	1.9	3.8	5.1	6.1	6.5
4:10- 4:20...	1.277	0.32	26.4	428.4	.4510	3.5	33.5	6.5	2.98	0.56	-3.4	0.0	0.0	2.	3.9	5.1	6.0	6.5
4:30- 4:35.	1.283	0.32	26.3	432.4	.4530	3.6	33.5	6.5	2.99	0.56	....	....						
Averages...	1.289	0.32	26.7	426.1	.4521	3.6	34.0	6.5	2.99	0.55	-3.6	0.0	0.0	1.9	3.8	5.1	6.0	6.5
August 6, 1906.								c			c							
4:56- 5:00 ..	1,284	0.32	15.1	441.2	.2550	2.4	36.2	6.5	[2]3.07	0.44	2.9	-1.1	2.0	3.9	5.0	5.7	6.2	6.5
5:15- 5:20...	1.288	0.36	14.5	470.0	.2565	2.4	36.5	6.5	3.08	0.44	-3.2	-1.4	2.0	3.9	5.0	5.6	6.2	6.5
Averages....	1.286	0.34	11.8	455.6	.2558	2.4	36.4	6.5	3.08	0.44	-3.0	-1.2	2.0	3.9	5.0	5.6	6.2	6.5
August 6, 1906.								c			c							
-5:30- 5:33...	1.298	0.38	7.94	492.8	[1],0000	2.4	30.0	6.5	[2]2.84	0.73	3.1	4.2	5.4	6.0	6.2	6.4	6.5	6.5
August 7, 1906.								o			c							
10:15-10: 0...	1.297	0.28	42.7	375.2	.6518	6.4	5.0	5.1	[2]1.98	1.74	5.1	....	0.0	-0.2	2.2	3.6	4.9	4.9
11:00-11:10...	1.300	0.30	42.6	386.2	.6478	6.3	5.	5.0	1.98	1.74	4.5	....	....	....	1.8	3.4	4.8	4.8
11:23 11:33...	1.308	0.30	43.4	383.0	.6405	6.2	6.2	6.5	2.02	1.69	5.5	0.1	0.8	1.1	3.4	4.9	6.2	6.3
11:45-11:55...	1.319	0.29	38.7	405.8	.6385	6.3	6.0	6.5	2.02	1.68	5.6	0.1	0.4	0.7	3.2	4.8	6.2	6.2
12:10-12:20...	1.312	0.32	39.1	418.0	.6410	6.3	6.0	6.5	2.02	1.68	5.6	0.2	0.9	0.8	3.2	4.9	6.2	6.2
Averages....	1.307	0.30	41.3	393.6	.6439	6.3	5.6	5.9	2.00	1.71	5.3	0.1	0.4	0.5	2.8	4.3	5.7	5.7

[1] 0.15 ft of water on left column of mercury manometer all day.

[2] 0.1 ft. of water on left column of mercury manometer all day.

TABLE XVI.—Continued.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION.

TIME.	Average revolutions of pump per minute.	Field current. (Amperes)	POWER READINGS.		Average head on weir.	Suction head. (Inches of mercury.)	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.							
			Average current.	Average. E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer.		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
									Left.	Right.								
	R.P.M.	Amps.	volts.	E.M.F.	Ft.	In.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
August 7, 1906.								o			c							
5:00- 5:05...	1,311	0.31	41.1	393.6	.6328	6.2	5.0	5.5	[2]2.00	1.73	4.8	....	0.1	-0.1	2.4	3.9	5.2	5.3
5:10- 5:15...	1,3 3	....	38.7	409.6	.6305	6.2	6.0	6.5	2.03	1.69	5.4	0.0	0.7	0.4	3.3	4.8	6.2	6.2
Averages....	1,312	0.31	39.9	401.6	.6316	6.2	5.5	6.0	2.02	1.71	5.2	0.0	0.4	0.2	2.8	4.4	5.6	5.8
August 7. 1906.								c			c							
5:30- 5:35...	1,278	....	8.25	457.2	[1].0000	2.4	29.2	6.5	[2]2.82	0.75	2.7	4.2	5.3	5.9	6.1	6.4	6.4	6.5

[1] 0.15 ft. of water on left column of mercury manometer all day.
[2] 0,1 ft. of water on left column of mercury manometer all day.

TABLE XVII.

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER SUCTION. (Slight air leakage, condition No. 2).

DISCHARGE CHAMBER. FORM SPIRAL, CROSS-SECTION CIRCULAR: THROAT NEARLY CLOSED (1⅛" x ½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛" x 2⅛"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED. AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,290 REVOLUTIONS PER MINUTE.

TIME.	Reference No.	Revolutions per minute.	Field current.	POWER READINGS.		Electrical horse power.	Horse power input.	Suction head.	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge cubic feet per second.	Horse power output.	Efficiency.	HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER.							
																	Water Gages.							
				Average current.	Average E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer.						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
		R.P.M	Amp.	Amp.	Volts.	E.H.P	B.H.P	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		H. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
August 3, 1906. 10:35—12:07 and............ August 4, 1906. 9:00—:10	1	1,300	0.30	41.5	399.6	22.2	18.3	—7.2	10.8	c 6.5	11.2	18.4	.6419	2.52	5.3	28.8	c 4.6 9.3	1.7 6.4	0.4 5.1	1.3 6.0	.6 8.3	5.0 9.7	6.4 11.1	6.4 11.1
August 4, 1906 10:30—3:17.....	2	1,284	0.31	40.7	391.1	21.3	17.6	—7.1	15.6	6.5	16.4	23.5	.6361	2.49	6.6	37.8	c 3.2 13.1	2.4 12.3	0.2 10.1	2.1 12.0	4.1 14.0	5.2 15.1	6.5 16.4	6.4 16.
August 4, 1906. 3:30—4:25......	3	1,274	0.34	35.7	432.1	20.7	16.7	—6.7	20.5	c 6.5	20.6	27.3	.6225	2.41	7.5	44.7	c 2.0 16.1	2.1 16.2	0.1 14.2	2.0 16.1	4.0 1 .1	5. 9.3	6.4 20.5	6.4 20.5
August 4, 1906. 4:28—5:25......	4	1,272	0.36	32.5	440.8	19.2	15.1	—6.2	24.9	c 6.5	25.0	31.2	.59 4	2.28	8.1	53.6	c 0.2 18.	1.6 20.1	—0.1 18.4	2.0 20.5	3.9 22.4	5. 3.7	6. 24.9	6.4 24.9
August 4, 1906. 5:30—5:35......	5	1,266	0.38	27.6	472.4	17.6	13.3	—5.4	29.5	.....	29.1	34.5	.5355	1.95	7.6	57.5	......	.....	.....	.....	.....	.....	.....	.....

TABLE XVII.—Continued.

SUMMARY SHEET; RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

TIME.	Reference No.	Revolutions per minute.	Field current.	POWER READINGS.		Electrical horse power.	Horse power input.	Suction head.	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge (cubic feet per second).	Horse power output.	Efficiency.	HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER.							
																	Water Gage.							
				Average current.	Average. E. M. F.				Pressure gage.	Water gage No. 9.	Mercury manometer.						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.
		R.P.M	Amp.	Amp.	Volts.	E.H.P	B.H.P	Ft	Ft.	Ft.	Ft	Ft.	Ft.		H. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
August 6, 1906. 10:30—12:10....	6	1,285	0.30	35.6	393.7	18.7	15.1	—5.5	30.1	c 6.5	30.4	35.9	.5518	2.03	8.3	54.7	c —2.0 21.9	0.9 24.8	— .5 23.4	1.7 25.6	3.7 27.6	5.1 29.0	6.2 30.1	6.4 30.3
August 6, 1906. 12:16—4:35.....	7	1,289	0.32	26.7	426.1	15.3	11.4	—4.1	34.0	c 6.5	33.9	38.0	.4521	1.52	6.6	57.6	c —3.6 23.8	0.0 27.4	0.0 27.4	1.9 29.3	3.8 1.2	5.1 32.5	6.0 33.4	6.5 33.9
August 6, 1906. 4:56—5:20......	8	1,286	0.34	14.8	455.6	9.0	5.3	—2.7	36.4	c 6.5	36.5	39.2	.2558	0.61	2.7	51.0	c —3.0 27.0	—1.2 28.8	2.0 32.0	3.9 33.9	5.0 35.0	5.6 35.6	6.2 36.2	6.5 36.5
August 6, 1906. †5:30—5:33.....	9	1,298	0.38	7.94	492.8	5.3	1.0	—2.6	30.0	c 6.5	29.6	32.2	.0000	0.00	0.0	00.0	c 3.1 26.2	4.2 27.3	5.4 28.5	6.0 29.	6.2 29.3	6.4 29.5	6.5 29.6	6.5 29.6
August 7, 1906. 10:15—12:20....	10	1,307	0.30	41.3	393.6	21.8	18.0	—7.2	5.6	o 5.9	5.8	13.0	.6439	2.53	3.7	20.8	o 5.3	0.1	0.4	0.5	2.8	4.3	5.7	5.7
August 7, 1906. 5:00—5:15......	11	1,312	0.31	39.9	401.6	21.5	17.6	—7.1	5.5	o 6.0	6.1	13.2	.6316	2.47	3.7	21.1	o 5.2	0.0	0.4	0.2	2.8	4.4	5.6	5.8
August 7, 1906. †5:30—5:35	12	1,278	......	8.25	457.2	5.0	1.1	—2.6	2 .2	c 6.5	29.0	31.6	.0000	0.00	0.0	00.0	c 2.7 25.2	4.2 26.7	5.3 27.8	5.9 28.4	6.1 28.6	6.4 28.9	6.4 28.9	6.5 29.0

TABLE XVIII.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER; FORM SPIRAL, CROSS-SECTION CIRCULAR, THROAT NEARLY CLOSED (1¼" x ½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1¼" x 2"). IMPELLER: 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATER WAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,120 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head. (Pressure).	DISCHARGE HEAD.				READING OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.								Reading of water gage No. a for balance chamber.
		Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer.		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
								Left.	Right.									
	R.P.M.	Amps.	Volts.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Dec. 9, 1907.					o		c			c								o
4:00—4:10......	1.114	30.2	393.7	.6400	1.4	17.9	6.5	4.03	2.92	4.8	2.5	3.7	3.9	5.2	6.3	7.1	6.5	4.2
4:15—4:25......	1.124	30.6	403.9	.6445	1.4	18.2	6.0	4.03	2.92	4.4	2.[illegible]	3.2	3.5	4.8	5.7	6.3	5.8	4.2
Averages....	1,119	30.5	398.8	.6422	1.4	18.1	6.2	4.03	2.92	4.6	2.3	3.4	3.7	5.0	6.0	6.7	6.2	4.2
Dec. 9, 1907.					o		c			c								o
4:30—4:45......	1.114	30.2	391.4	.6110	1.8	22.9	5.8	4.22	2.71	2.0	0.4	2.2	3.0	4.4	5.4	6.1	5.8	4.9
4:45—5:00......	1.112	30.6	378.1	.6060	1.8	22.7	5.5	4.21	2.71	1.8	0.1	2.0	2.7	4.1	5.1	5.7	5.5	4.8
Averages....	1,113	30.4	384.8	.6085	1.8	22.8	5.6	4.22	2.71	1.9	0.2	2.1	2.8	4.2	5.2	5.9	5.6	4.8
Dec. 9, 1907.					o		c			c								o
5:20—5:30......	1,123	27.0	423.4	.5560	2.5	28.2	6.2	4.39	2.50	— .9	—1.3	1.7	2.9	4.3	5.5	6.2	6.2	5.9
5:30—5:40......	1,129	26.5	449.6	.5580	2.5	28.7	6.1	4.39	2.50	—1.1	—1.5	1.5	2.8	4.2	5.4	6.1	6.[illegible]	5.9
Dec. 10, 1907.																		
10:50—11:00....	1,122	31.0	367.2	.5545	2.6	27.2	6.0	4.39	2.50	1.0	—1.4	1.6	2.8	4.2	5.3	6.0	6.0	5.9
Averages....	1.125	28.0	413.4	.5562	2.5	28.7	6.1	4.39	2.50	— .0	—1.4	1.6	2.8	4.2	5.4	6.1	6.1	5.9

TABLE XVIII—Continued.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head. (Pressure).	DISCHARGE HEAD.				READING OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.								Reading of water gage No. a for balance chamber.
		Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer. Left.	Mercury manometer. Right.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
	R.M. P.	Amps.	Volts.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Dec. 10, 1907.					o		c			c								o
11:10—11:25....	1,123	25.6	364.2	.4425	3.7	33.5	6.1	4.54	2.33	—3.2	—2.2	1.2	2.5	4.1	5.2	5.8	6.1	6.8
11:25—11:35....	1,124	25.4	366.3	.4430	3.7	33.5	6.2	4.57	2.32	—3.2	—2.2	1.2	2.7	4.2	5.3	6.0	6.2	6.8
Averages....	1,124	25.6	365.3	.4428	3.7	33.5	6.2	4.56	2.32	—3.2	—2.2	1.2	2.6	4.2	5.2	5.9	6.2	6.8
Dec. 10, 1907.					o		c			c								o
11:45—12:00....	1,121	22.4	411.2	.4020	3.9	34.5	6.1	4.59	2.26	—3.5	—2.2	1.1	2.6	4.2	5.2	5.8	6.1	7.3
12:05—12:10....	1,122	21.2	423.0	.4040	3.9	34.5	6.1	4.61	2.27	—3.6	—2.3	.1	2.5	4.1	5.2	5.8	6.1	7.3
Averages....	1,122	21.8	417.1	.4030	3.9	34.5	6.1	4.60	2.26	—3.6	—2.2	1.1	2.6	4.2	5.2	5.8	6.1	7.3
Dec. 10, 1907.					o		c			c								o
2:30—2:40......	1,122	19.6	422.2	.3495	4.3	36.7	6.4	4.63	2.23	—3.5	—1.4	†1.8	3.2	4.7	5.6	6.2	6.4	7.4
2:50—2:55......	1,136	9.5	422.6	.3540	4.3	36.7	....	....	2.21	....	....	....	....	....	....	....	....	....
3:00—3:20......	1,121	18.7	434.2	.3530	4.2	36.7	....	....	2.22	....	....	....	....	....	....	....	....	....
3:25—3:40......	1,138	20.4	411.2	.3560	4.2	36.9	6.3	4.68	2.19	—4.3	—2.1	1.3	3.0	4.5	5.4	6.0	6.3	7.8
Averages....	1,129	19.5	422.5	.3532	4.3	36.7	6.4	4.65	2.21	—3.9	—1.8	1.6	3.1	4.6	5.5	6.1	6.4	7.6
Dec. 11, 1907.					o													
11:40—11:50....	1,111	28.0	423.3	.6080	1.8	23.7	....	4.18	2.75	... ...	....	....	....	....	....	....	....	....
11:50—11:55....	1,110	28.0	418.0	.6105	1.8	23.7	... ...	4.18	2.74	....	....	....	....	....	....	....	....	....
Averages....	1,110	28.0	420.6	.6092	1.8	23.7	....	4.18	2.74	....	....	....	....	....	....	....	....	....

Dec. 11, 1907.					o													
12:05—12:10....	1,128	27.1	433.9	.5580	2.6	28.9	....	....	2.49	....	....	....	....	....	....	....	....	....
12:15—12:20....	1,121	26.1	437.3	.5540	2.6	28.7	....	4.37	2.52	....	....	....	....	....	....	....	....	....
Averages....	1,124	26.5	435.7	.5560	2.6	28.8	....	4.37	2.51	....	....	....	....	....	....	....	....	....
Dec. 11, 1907.					o													
12:25—12:30....	1,121	21.5	441.5	.4435	3.6	32.5	....	4.52	2.35	....	....	....	....	....	....	....	....	....
Dec. 12, 1907.					o													o
†10:30—10:40...	1,112	9.5	411.7	.0000	5.3	29.7	....	4.43	2.46	....	....	....	....	....	....	....	....	8.0
†10:40—10:50...	1,116	9.5	425.8	.0000	5.3	29.7	....	4.43	2.46	....	....	....	....	....	....	....	....	8.0
Averages....	1,114	9.5	418.7	.0000	5.3	29.7	....	4.43	2.46	....	....	....	....	....	....	....	....	8.0

TABLE XIX.

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER, FORM SPIRAL, CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED (1¼"x½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1¼"x2¼") IMPELLER, 12 VANES RADIAL, WITH ENTRANCE CURVED; AREA OF CROSS-SECTION OF WATER-WAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,120 REVOLUTIONS PER MINUTE.

TIME.	Reference No.	Revolutions per minute.	POWER READINGS.		Electrical horse-power.	Horse-power input.	Suction head pressure.	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge cubic feet per second.	Horse-power output.	Efficiency.	HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER. Water gages.								Balance chamber pressure gage No.a
			Current.	E. M. F.				Press. gage.	Water gage No. 9.	Mercury manometer						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
		R.P.M	Amps	Volts.	E.H.P	B.H.P	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	
Dec. 9, 1907. 4:00—4:25......	1	1,119	30.5	398.8	16.3	12.4	o 1.4	18.1	c 6.2	18.0	16.6	6,442	2.54	4.8	38.6	c 4.6 16.4	2.3 14.1	3.4 15.2	3.7 15.5	5.0 16.8	6.0 17.	6.7 18.5	6.2 18.0	o 4.2 .....
Dec. 9, 1907. 4:30—5:00......	2	1,113	30.4	384.8	15.7	11.7	o 1.8	22.8	c 5.6	23.3	21.5	6,085	2.33	5.7	48.6	1.9 19.6	0.2 17.9	2.1 9.8	2.8 20.5	4.2 21.9	5.2 22.9	5.9 23.6	5.6 23.3	o 4.8 .....
Dec. 9, 1907. 5:20—5:40......	3	1,125	28.0	413.4	15.5	11.5	o 2.5	28.7	c 6.1	28.2	25.7	5,562	2.04	6.0	51.8	c —1.0 21.1	—1.4 20.7	1.6 23.7	2.8 24.9	4.2 26.3	5.4 27.5	6.1 28.2	6.1 28.2	o 5.9 .....
Dec. 10, 1907. 11:10—11:35....	4	1,124	25.6	365.3	12.5	8.4	o 3.7	33.5	c 6.2	32.7	29.0	4,428	1.47	4.8	57.6	c —3.2 23.3	—2.2 24.3	1.2 27.	2.6 29.1	4.2 30.7	5.2 31.7	5.9 32.4	6.2 32.7	o 6.8 .....
Dec. 10, 1907. 11:45—12:10....	5	1,122	21.8	417.1	12.2	8.1	o 3.9	34.5	c 6.1	34.1	30.2	4,030	1.29	4.4	54.6	c —3.6 24.4	—2.2 25.8	1.1 29.1	2.6 30.6	4.2 32.2	5.2 33.2	5.8 33.8	6.1 34.1	o 7.3 .....
Dec. 10, 1907. 2:30—3:40......	6	1,129	19.5	422.5	11.1	7.0	o 4.3	36.7	c 6.4	35.5	31.2	3,532	1.03	3.8	53.7	c —3.9 25.2	—1.8 27.3	1.6 30.7	3.1 32.2	4.6 33.7	5.5 34.6	6.1 35.	6.4 35.5	o 7.6 .....

Dec. 11, 1907. 11:40—11:55....	7	1,110	28.0	420.6	15.8	11.	o 1.8	23.	.....	22.3	20.5	6,032	2.33	5.4	45.6	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 11, 1907. 12:05—12:20....	8	1,124	26.5	435.	15.5	11.5	o 2.6	28.8	.....	27.8	25.2	5,560	2.04	5.8	50.8	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 11, 1907. 12:25—12:30....	9	1,121	21.5	441.5	12.7	8.6	o 3.6	32.5	.....	31.8	8.2	4,435	1.48	4.7	55.2	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 12, 1907. 10:30—10:50....	10	1,114	9.5	418.7	5.3	0.8	o 5.3	29.7	.....	20.3	24.0	0000	0.00	0.0	55.2	......	.....	.....	.....	.....	.....	.....	.....	o 8.0
Dec. 11, 1907. 4:20—4:40......	[1]11a	1,118	20.2	391.5	10.6	6.4	o 4.2	30.7	.....	29.7	25.5	3,540	1.06	3.1	48.0	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 11, 1907. 4:40—4:50......	11	1,120	20.5	406.0	11.	7.0	o 4.1	33.8	.....	34.4	30.3	3,770	1.16	4.0	56.9	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 11, 1907. 5:00—5:10......	12	1,129	31.5	405.2	17.1	13.2	o 1.2	.....	.....	17.2	16.0	6,485	2.56	4.6	35.2	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 11, 1907. 5:20—5:30......	[1]12a	1,123	28.6	435.8	15.7	12.8	o 1.2	.....	.....	15.2	15.0	6,205	2.40	4.2	31.9	......	.....	.....	.....	.....	.....	.....	.....	.....
Dec. 12, 1907. 11:50—11:55....	[2]10a	1,118	9.9	409.2	5.4	0.9	o 4.8	.....	.....	22.0	17.2	0000	0.00	0.0	55.2	......	.....	.....	.....	.....	.....	.....	.....	.....

[1] Air under pressure admitted into suction pipe through ¼" iron pipe on suction piezometer.
[2] Air under pressure admitted into balance chamber through ⅛" iron pipe.

TABLE XX.

OBSERVATIONS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER, FORM SPIRAL, CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED (1⅛"x½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x2⅛"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1,300 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on Weir.	Suction head. (Pressure.)	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.								Reading of water gage No. a. for balance chamber.
		Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer.										
								Left.	Right.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
	R.P.M.	Amps.	Volts.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Dec. 3, 1907.					o		c			c								o
11:10..........	1,290	46.0	371.3	.6785	....	17.8	6.3	4.04	2.91	3.3	—0.5	1.9	2.8	4.6	6.1	6.7	6.3	4.6
11:27..........	1,287	46.0	364.8	.6802	0.7	18.5	6.1	4.04	2.90	3.0	—0.8	1.6	2.[illegible]	4.2	5.7	6.5	6.0	4.5
Averages.	1,288	46.0	368.0	.6794	0.7	18.1	6.2	4.04	2.90	3.2	—0.6	1.8	2.7	4.4	5.9	6.6	6.2	4.6
Dec. 3, 1907.					o		c			c								o
11:45..........	1,294	45.1	379.7	.6554	0.9	24.2	6.2	4.24	2.68	1.2	—1.8	0.8	2.1	4.1	5.0	6.5	6.2	5.0
12:00..........	1,308	43.2	465.3	.6688	0.8	24.2	6.1	4.25	2.66	1.0	—2.1	0.6	2.0	4.0	4.9	6.4	6.0	5.0
Averages.	1,301	44.1	423.0	.6671	0.9	24.2	6.2	4.24	2.67	1.1	—2.0	0.7	2.0	4.0	5.0	6.4	6.1	5.0
Dec. 3, 1907.					o		c			c								o
12:15..........	1,300	43.4	395.7	.6464	1.2	29.5	6.1	4.42	2.46	—1.3	—3.3	0.1	1.6	3.7	5.3	6.3	6.2	5.5
12:30..........	1,306	43.5	408.0	.6490	1.3	29.7	6.1	4.43	2.45	—1.2	—3.3	0.0	1.6	3.7	5.3	6.2	6.0	5.5
Dec. 4, 1907.																		
3:05..........	1,298	46.1	397.8	.6448	1.3	29.2	6.5	4.42	2.46	—1.1	—3.1	0.3	1.9	3.9	5.6	6.6	6.4	5.6
Averages.	1,301	44.3	400.5	.6434	1.3	29.5	6.2	4.42	2.46	—1.2	—3.2	0.1	1.7	3.8	5.4	6.4	6.2	5.5

Dec. 4, 1907.					o													o
3:15	1,308	44.2	401.8	.6078	1.9	34.7	....	4.63	2.23	....	....	....	....	....	....	....	....	6.5
3:35	1,310	46.1	389.0	.6115	1.8	34.8	....	4.61	2.22	....	....	....	....	....	....	....	....	....
Averages	1,309	45.2	395.4	.6096	1.9	34.8	....	4.64	2.22	....	....	....	....	....	....	....	....	6.5
Dec. 4, 1907.					o													o
3:45	1,305	40.6	404.3	.5325	2.9	39.7	....	4.81	2.02	....	....	....	....	....	....	....	....	7.5
Dec. 6, 1907.					o		c			c								o
10:53	1,302	46.2	372.8	.6168	1.8	34.6	6.1	4.55	2.32	—2.4	—4.5	—0.4	1.6	3.7	5.1	6.2	6.1	6.5
11:15	1,308	46.4	352.4	.6131	1.8	34.3	6.1	4.58	2.28	—3.5	—4.5	—0.5	1.4	3.5	5.1	6.1	6.0	6.5
Averages	1,305	46.3	362.6	.6148	1.8	34.4	6.1	4.56	2.30	—3.0	—4.5	—0.4	1.5	3.6	5.1	6.2	6.0	6.5
Dec. 6, 1907.					o		c			c								o
11:40	1,297	38.4	381.1	.5421	2.8	39.7	6.5	4.79	2.05	—5.6	—4.5	—0.5	1.5	3.7	5.3	6.2	6.5	7.4
12:05	1,298	36.1	404.6	.5403	2.8	39.7	6.6	4.79	2.05	—5.8	—4.8	—0.5	1.6	3.8	5.3	6.3	6.5	7.3
Averages	1,298	37.2	392.8	.5412	2.8	39.7	6.6	4.79	2.05	—5.7	—4.6	—0.5	1.6	3.8	5.3	.2	6.5	7.4
Dec. 7, 1907.					o		c			c								o
10:20	1,305	30.1	401.4	.4198	3.7	43.7	6.6	4.97	1.85	—6.8	—4.4	0.0	2.0	4.1	5.5	6.1	6.5	6.8
10:50	1,314	30.1	404.0	.4220	....	43.9	....	5.00	1.82	....	....	....	....	....	....	....	....	....
1 :05	1,297	30.0	372.2	.4184	3.7	43.6	6.4	4.92	1.90	—6.8	—4.5	—0.1	2.1	4.0	5.3	6.0	6.3	6.6
Averages	1,305	30.1	392.5	.4201	3.7	43 7	6.5	4. 6	1.86	—6.8	—4.4	—0.0	2.0	4.0	5.4	6.0	6.4	6.7
Dec. 7, 1907.					o		c			c								o
11:25	1,313	24.3	411.2	.3366	4.0	45.2	6.5	5.04	1.78	—7.1	—3.6	0.5	2.8	4.3	5.4	6.0	6.4	7.5
12:05	1,294	21.9	428.1	.3320	4.2	44.5	6.4	4.95	1.84	—6.6	—3.2	1.0	3.0	4.5	5.5	6.1	6.4	7.5
Averages	1,304	23.1	4 9.6	.3343	4.1	44.9	6.4	5.00	1.81	—6.8	—3.4	0.8	2.9	4.4	5.4	6 0	6.4	7.5
Dec. 7, 1907.					o		c			c								o
†12:40	1,307	11.3	439.2	.0000	5.6	38.7	5.4	4.76	2.07	0.9	2.9	4.3	4.9	5.3	5.4	5.3	5.3	9.6
Dec. 7, 1907.					o													
3:35	1,304	33.0	469.6	.5535	2.5	38.9	....	4.75	2.08	....	....	....	....	....	....	....	....	....
3:40	1,295	32.7	461.2	.5305	2.8	39.7	....	4.75	2.08	....	....	....	....	....	....	....	....	....
Averages	1,300	32.8	465.4	.5420	2.6	39.3	....	4.75	2.08	....	....	....	....	....	....	....	....	....

TABLE XXI.

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER. FORM SPIRAL. CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED (1⅛"x ½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x 2⅛"). IMPELLER; 12 VANES, RADIAL WITH ENTRANCE CURVED. AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,300 REVOLUTIONS PER MINUTE.

TIME.	Reference No.	Revolutions per minute.	POWER READINGS.		Electrical horse power.	Horse power input.	Suction head (pressure).	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge, cubic feet per second.	Horse power output.	Efficiency.	HYDRAULIC GRADIENT CENTER LINE OF DISCHARGE CHAMBER.								Balance chamber press. gage No. a.
																Water Gages.								
			Current.	E. M. F.				Press. gage.	Water gage No. 9.	Mercury manometer						No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
		R.P.M	Amps.	Volts.	E.H.P	B.H.P	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		H. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Dec. 3, 1907. 11:10.........	1	1,288	46.0	368.0	22.7	18.5	o 0.7	18.1	c 6.2	18.5	17.8	.6794	2.75	5.5	30.0	c 3.2 15.5	—0.6 1.7	1.8 14.1	2.7 15.0	4.4 16.7	5.9 18.2	6.6 18.9	6.2 18.5	o 4.6 ....
Dec. 3, 1907. 11:45.........	2	1,3 1	44.1	423.0	25.	20.8	o 0.9	24.2	c 6.2	24.0	23.1	.6671	2.68	7.0	33.8	c 1.1 8.9	2.0 15.8	0.7 18.5	2.0 19.8	4.0 29.8	5.0 22.8	6.4 24.2	6.1 23.9	o 5.0 ....
Dec. 3, 1907. 12: 5.........	3	1,30	44.3	400.	23.8	19.6	o 1.3	29.5	c 6.2	29.1	27.8	.6467	2.55	8.0	41.0	c 1.2 21.7	—3.2 19.7	0.1 23.0	1.7 24.6	3.8 26.7	5.4 28.3	6.4 29.3	6.2 29.1	o 5.5 ....
Dec. 4, 1907. 3:15..........	4	1,305	45.2	395.4	24.0	19.8	o 1.9	34.8	......	35.1	33.2	.6096	2.34	8.8	44.5	......	......	......	......	......	......	......	......	o 6.5
Dec. 4, 1907. 3:45..........	5	1,305	40.6	404.3	22.0	17.9	o 2.9	39.7	......	40.0	37.1	.532	1.92	8.1	45.2	......	......	......	......	......	......	......	......	o 7.5
Dec. 6, 1907. 1 :53.........	6	1,305	46.3	362.6	22.5	18.3	o 1.8	34.4	c 6.1	33.	31.2	.6148	2.36	8.4	45.6	c —3.0 23.9	—4.5 22.4	—0.4 26.5	1.5 28.4	3.6 30.5	5.1 32.0	6.2 33.1	6.0 32.9	o 6.5 ....

Dec. 6, 1907. 11:40.........	7	1.298	.7.2	393.8	19.6	15.5	o 2.8	39.7	c 6.6	39.3	36.5	.5412	1.97	8.2	52.7	c −5.7 27.0	−4.6 28.1	−0.5 32.	1.6 31.1	3.8 36.5	5.3 38.0	6.2 38.9	6.5 39.2	o 7.4 ....
Dec. 7, 1907. 10:20.........	8	1.305	30.1	392.5	15.0	11.7	o 3.7	43.7	c 6.5	44.1	40.4	.4201	1.37	6.3	53.7	c −6.8 30.8	−4.4 33.2	0.0 37.6	2.0 39.6	4.0 41.6	5.4 43.0	6.0 43.6	6.4 44.0	o 6.7 ....
Dec. 7, 1907. 11:25.........	9	1.304	23.1	4 9.6	13.0	8.9	o 4.1	44.9	c 6.4	45.3	41.2	.3343	0.98	4.6	51.5	c −6.8 32.1	−3.4 35.5	0.8 39.7	2.9 41.8	4.4 43.3	5.4 44.3	6.0 44.9	6.4 45.3	o 7.5 ....
Dec. 7, 1907. +12:40........	10	1.307	11.3	439.2	6.7	2.3	o 5.6	38.7	c 5.4	38.6	33.0	.0000	0.00	0.0	0.0	c 0.9 34.1	2.9 36.1	4.3 37.5	4.9 38.4	5.3 38.5	5.4 38.6	5.3 38.5	5.3 38.5	o 9.6 ....

TABLE XXII.

OBSERVATIONS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER, FORM SPIRAL, CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED (1⅛"x½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛"x2⅛"). IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED. AREA AT CROSS-SECTION OF WATER WAY PRACTICALLY CONSTANT.

SPEED OF PUMP 1,500 REVOLUTIONS PER MINUTE.

TIME.	Average revolutions of pump per minute.	POWER READINGS.		Average head on weir.	Suction head (pressure).	DISCHARGE HEAD.				READINGS OF WATER GAGES FOR HYDRAULIC GRADIENT, CENTER LINE OF DISCHARGE CHAMBER.								Reading of water gage No. a. for balance chamber.
		Average current.	Average E. M. F.			Pressure gage.	Water gage No. 9.	Mercury manometer,		No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
								Left.	Right.									
	R.P.M.	Amps.	Volts.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Dec. 13, 1907.					o		c			c								o
11:40—.........	1,5 5	55.6	434.1	6840	0.6	[1]29.7	......	4.43	2.45	......	......	......	......	......	......	......	......	......
3:05—..........	1,485	49.5	482.7	6845	0.6	29.7	6.1	4.45	2.44	—2.1	—6.9	—1.8	0.2	2.9	4.6	6.1	5.9	5.9
3:25—..........	1,506	50.7	483.6	6832	0.6	29.7	6.4	4.44	2.44	—2.0	—7.2	—1.9	0.0	3.0	4.9	6.4	6.3	6.1
Averages	1,499	51.7	466.5	6839	0.6	29.7	6.2	4.44	2.44	—2.0	—7.0	—1.8	0.1	3.0	4.8	6.2	6.1	6.0
Dec. 13, 1907.					o		c			c								o
3:50—..........	1,516	52.1	475.0	6815	0.6	34.2	6.3	4.61	2.25	—3.8	—8.0	—2.3	0.3	3.0	4.9	6.3	6.2	6.2
4:25—..........	1,502	48.4	493.8	6805	0.7	34.2	6.3	4.61	2.25	—3.4	—7.6	—2.1	0.4	3.1	4.6	6.3	6.2	6.2
Averages	1,509	50.2	484.4	6810	0.7	34.2	6.3	4.61	2.25	—3.6	—7.8	—2.2	0.4	3.0	4.8	6.3	6.2	6.2
Dec. 13, 1907.					o		c			c								o
5:20—..........	1,510	56.9	448.0	7015	0.3	19.7	6.4	4.08	2.86	1.9	—3.2	—0.8	—1.7	2.0	4.6	6.2	6.1	5.6
Dec. 14, 1907.																		
10:45—.........	1,498	55.0	436.1	6965	0.3	19.2	6.2	4.08	2.87	1.6	—3.0	—0.6	—1.1	2.3	4.5	6.1	5.9	5.6
Averages	1,504	56.0	442.0	6990	0.3	19.4	6.1	4.08	2.86	1.8	—3.1	—0.7	—1.4	2.2	4.6	6.2	6.0	5.6

Dec. 14, 907.					o		c			c								o
11:00—.........	1,493	55.6	423.4	6870	0.5	25.7	6.4	4.30	2.60	—1.1	—6.2	—1.5	—0.1	3.0	6.0	6.5	6.3	5.9
11;30—.........	1,502	55.3	431.6	6855	0.5	25.7	6.7	4.30	2.60	—0.5	—5.8	—1.2	0.0	3.1	5.2	6.6	6.5	6.0
Averages	1,498	55.4	427.0	6862	0.5	25.7	6.6	4.30	2.60	—0.8	—6.0	—1.4	0.0	3.0	5.1	6.6	6.4	6.0
Dec. 16, 1907.					o		c			c								o
10:50—.........	1,492	56.5	419.1	6625	1.0	39.4	....	4.79	2.04	....	....	....	....	....	....	....	....	....
3:50—..........	1,499	57.4	440.6	6620	1.1	38.7	6.3	4 80	2.04	—6.4	—8.3	—2.6	0.0	2.9	5.0	6.3	6.3	6.8
Dec. 17, 1907.																		
10:35—.........	1,504	55.8	461.7	6635	1.0	39.7	6.4	4.80	2.04	—6.5	—8.3	—2.6	0.0	2.9	5.1	6.4	6.4	6.8
Averages	1,498	56.5	440.5	6627	1.0	39.3	6.4	4.80	2.04	—6.4	—8.3	—2.6	0.0	2.9	5.0	6.4	6.4	6.8
Dec. 17, 1907.					o		c			c								o
10:55—.........	1,503	57.1	437.2	6180	1.8	45.2	6.6	5.01	1.77	....	....	....	0.0	2.9	5.1	6.3	6.5	7.8
11:25 —.........	1,512	54.5	446.8	6200	1.8	45.7	6.7	5.00	1.78	—8.6	—8.7	—3.0	0.0	2.9	5.	6.5	6.7	7.8
11:55—.........	1,504	53.2	449.3	6155	1.7	45.2	6.7	5.03	1.78	—8.6	—8.7	—3.2	0.0	2.9	5.2	6.5	6.7	7.8
Averages	1,506	55.0	444.4	6178	1.8	45.4	6.7	5.01	1.78	—8.6	—8.7	—3.1	0.0	2.9	5.2	6.4	6.6	7.8
Dec. 17, 1907.					o		c			c								o
2:35—..........	1,506	48.6	469.7	5515	2.7	50.4	6.7	5.18	1.58	9.7	—8.4	—2.8	0.0	3.0	5.0	6.2	6.7	8.7
3:30—..........	1,505	53.3	433.8	5515	2.7	50.2	6.7	5.20	1.59	—9.1	—8.1	—3.0	0.0	3.0	4.9	6.2	6.7	8.7
Averages	1,506	50.8	451.8	5515	2.7	50.3	6.7	5.19	1.58	—9.4	—8.2	—2.9	0.0	3.0	5.0	6.2	6.7	8.7
Dec. 17, 1907.					o		c			c								o
4:25—.........	1,510	35.5	463.6	4155	4.0	55.7	6.5	5.41	1.38	—11.4	—7.7	—2.5	0.3	3.2	5.1	6.0	6.5	9.9
Dec. 18, 1907.																		
10:45—.........	1,503	35.7	471.8	4175	3.9	55.7	6.2	5.37	1.39	—11.8	—8.2	—2.8	0.0	2.8	4.7	5.8	6.2	9.8
11:10—.........	1,505	33.6	471.2	4170	3.8	55.7	....	5.35	1.40	....	....	....	....	....	....	....	....	....
Averages	1,506	34.9	468.8	4167	3.9	55.7	6.3	5.38	1.39	—11.6	—8.0	—2.6	+0.2	3.0	4.9	5.9	6.4	9.8
Dec. 18, 1907.					o		c			c								o
11:25—.........	1,496	27.9	461.1	3540	4.3	57.7	6.2	5.43	1.32	—11.2	—6.6	—1.2	1.5	3.6	5.0	5.8	6.2	10.3
11:45—.........	1,502	28.1	462.0	3540	4.2	57.7	6.2	5.43	1.32	—10.9	—6.3	—1.1	1.5	3.6	4.9	5.7	6.2	10.1
Averages	1.499	28.0	461.6	3540	4.3	57.7	6.2	5.43	1.32	—11.0	—6.4	—1.2	1.5	3.6	5.0	5.8	6.2	10.2
Dec. 18, 1907.					o		c			c								o
12:00—.........	1,502	12.4	457.4	0000	5.7	49.2	6.5	5.14	1.65	0.3	2.9	4.8	5.6	6.1	6.3	6.4	6.5	11.0
†12:20—.........	1,510	12.2	461.2	0000	5.7	49.2	6.4	5.14	1.65	0.3	2.9	4 7	5.5	6.0	6.2	6.4	6.4	11.0
Averages	1,506	12.3	459.3	0000	5.7	49.2	6.4	5.14	1.65	0.3	2.9	4.8	5.6	6.0	6.2	6.4	6.4	11.0

TABLE XXIII.

SUMMARY SHEET: RESULTS OF EXPERIMENTS WITH A SIX INCH HORIZONTAL CENTRIFUGAL PUMP. ENTRANCE TO PUMP UNDER PRESSURE.

DISCHARGE CHAMBER; FORM SPIRAL, CROSS-SECTION CIRCULAR; THROAT NEARLY CLOSED (1⅛"x½"). VORTEX, RECTANGULAR IN CROSS-SECTION (1⅛ x2¼")
IMPELLER, 12 VANES, RADIAL WITH ENTRANCE CURVED, AREA OF CROSS-SECTION OF WATERWAY PRACTICALLY CONSTANT.

SPEED OF PUMP, 1,500 REVOLUTIONS PER MINUTE.

TIME.	Reference No.	Revolutions per minute.	POWER READINGS.		Electrical horse power.	Horse power input.	Suction head (pressure).	DISCHARGE HEAD.			Total head.	Head on weir.	Discharge, cubic feet per second.	Horse power output.	Efficiency.	HYDRAULIC GRADIENT. CENTER LINE OF DISCHARGE CHAMBER.								Balance chamber pressure, gage No. a.
			Current.	E. M. F.				Press. gage.	Water gage No. 9.	Mercury manometer.						Water Gages.								
																No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.	No. 7.	No. 8.	
		R.P.M	Amps.	Volts.	E H.P	B.H.P	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.		H. P.	%	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.	Ft.
Dec. 13, 1907. 11:40.	1	1.499	51.7	466.5	32.4	27.2	o 0.6	29.7	c 6.2	29.6	29.0	.6839	2.77	9.1	33.4	c —2.0 21.4	—7.0 16.4	—1. 21.6	0.1 23.5	3.0 26.4	4.8 28.2	6.2 29.6	6.1 29.5	o 6.0
Dec. 13, 1907. 3:50........	2	1,509	50.2	484.4	32.6	27.4	o 0.7	34.2	c 6.3	34.4	33.7	.6810	2.75	10.5	38.3	c —3.6 24.5	—7.8 20.3	—2.2 25.9	0.4 28.5	3.0 31.1	4.8 32.9	6.3 34.4	6.2 34.3	o 6.2
Dec. 13, 1907. 5:20	3	1,504	56.0	442.0	33.2	28.1	o 0.3	19.4	c 6.1	19.5	19.2	.6992	2.86	6.2	28.0	c 1.8 15.2	—3.1 10.3	—0.7 2.7	—1.4 12.0	2.2 15.6	4.6 18.0	6.2 19.6	6.0 19.4	o 5.6
Dec. 14, 1907. 11:00.......	4	1 498	55.4	42 .0	31.8	26.6	o 0.5	25.7	c 6.6	25.7	25.2	.6862	2.78	8.0	30.1	c —0.8 18 3	—6.0 13.1	—1.4 17.7	0.0 19.1	3.0 22.1	5.1 24.2	6.6 25.7	6.4 25.5	o 6.0
Dec. 16, 1907. 10:50......	5	1 498	56.5	440.5	33.4	28.1	o 1.0	39.3	c 6.4	39.6	38.6	.6627	2.65	11.6	41.3	c —6.4 26.8	—8.3 24.9	—2.6 30.6	0.0 33.2	2.9 36.1	5.0 38.2	6.4 39.6	6. 39.6	o 6.8
Dec. 17, 1907. 10:35.......	6	1,506	55.0	444.4	32.8	27.7	o 1.8	45.4	c 6.7	45.7	43.9	.6178	2.38	11.9	43.0	c —8.6 30.4	—8.7 30.3	—3.1 35.9	0.0 39.0	2.9 41.9	5.2 44.2	6.4 45.4	6.6 45.6	o 7.8

Dec. 17, 1907. 2:35........	7	1.506	50.8	451.8	30.8	25.7	o 2.7	59.3	c 6.7	50.4	47.7	.5515	2.01	10.9	42.4	c -9.4 34.3	-8.2 35.5	-2.9 40.8	0.0 43.7	3.0 46.7	5.0 48.7	6.2 49.9	6.7 50.4	o 8.7
Dec. 18, 1907. 10:45.......	8	1.505	34.9	465.8	21.9	17.0	o 3.9	55.7	c 6.3	55.5	51.6	.4167	1.35	7.9	46.1	c -11.6 37.6	-8.0 41.2	-2.6 6.6	-[illegible].0 49.4	3.0 52.2	4.9 54.1	5.9 55.1	6.4 55.6	o 9.8
Dec. 18, 190 . 11:25.......	9	1.490	28.0	461.6	17.3	12.6	o 4.3	57.7	c 6.2	57.3	53.0	.3540	1.05	6.4	50.7	c -11.0 40.1	-6.4 44.7	-1.2 49.9	1.5 52.6	3.6 54.7	5.0 56.1	5.8 56.9	6.2 57.3	o 10.2
Dec. 18, 1907. *12:00.......	10	1.505	12.3	459.3	7.6	2.9	o 5.7	49.[illegible]	c 6.4	49.1	43.4	.0000	0.00	0.0	[illegible]1.9	c .3 43.0	2.9 45.6	4.8 47.5	5.6 48.3	6.0 48.7	6.2 4[illegible].9	6.4 49.1	6.4 49.1	o 11.0

DISCUSSION OF RESULTS OF EXPERIMENTS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP

Effect of Leakage of Air into Pump

The leakage of air into the pump was first observed and made known by attaching a short glass tube to the upper side of the horizontal discharge pipe, Plate III, and providing the tube with a valve at the upper end. When air was leaking into the pump a portion of it would slowly collect in the glass tube, the rate of collection serving somewhat as a measure of the rate of leakage. At the time of making the first experiments with the circular case, Tables IV–IX, the amount of air leaking into the pump was thought to be so small as not materially to alter the results; but subsequent experiments showed the necessity of entirely eliminating the leakage of air into the pump. Plate XII shows the effect of air leakage, by a comparison of these first results with results of subsequent experiments taken with the entrance to the pump under pressure so that air leakage was prevented. The amount of air leakage, termed *"Air leakage, condition No. 1,"* in these first experiments could not be determined volumetrically as it was almost entirely leakage through the stuffing box of the pump shaft. An approximate indirect determination, however, was made as shown later, by placing the entrance to the pump under suction, putting a small iron box containing water around the stuffing box to prevent air leakage, and then admitting air to the suction side of the pump, under a known suction head, and through an opening of known size until, as shown by the discharge, air leakage condition No. 1 was practically duplicated.

The experiments, Tables XIV–XVII, entrance to pump under suction, were taken with the stuffing box of the pump shaft surrounded by water contained in a small galvanized iron box, so that air leakage at this point was practically eliminated. The results platted on Plate XIII, when compared with results with the entrance to the pump under pressure, Plate XIV, show evidence, however, of slight air leakage at some point. In the tables and plates this condition of slight air leakage has been termed *"Slight air leakage, condition No. 2."*

An approximate determination of the amounts of air leakage. under "*Air leakage, condition No. 1,*" was made from the following experiments, Table XXIV, taken for the purpose:

TABLE XXIV.

Time.	Experiment No.	Speed of pump.	Suction head pressure (+), suction (−)	Discharge head.	Total head.	Head on weir.	Discharge.	Discharge reduced to 15 ft. head.
April 29, 1908.		R. P. M.	Ft.	Ft.	Ft.	Ft.	Cubic ft. per sec.	Cubic ft. per sec.
11:00	1	1,120	+1.20	15.8	14.6	.6230	2.41	2.40
11:20	2	1,120	−4.2	14.1	18.3	.5770	2.16	2.30
11:30	3	1,126	−2.4	12.2	14.6	.5310	1.91	1.90
11:40	4	1,115	+1.0	15.8	14.8	.6300	2.45	2.44
11:50	5	1,115	+1.0	15.8	14.8	.6280	2.44	2.43
12:00	6	1,125	+1.0	15.9	14.9	.6280	2.44	2.43

The pump was kept running throughout the six experiments. In experiment No. 1 the entrance to pump was under pressure, the suction head being + 1.2 feet. This gave the normal discharge for the given speed and head without air leakage. The entrance to the pump was then put under suction, experiments Nos. 2 and 3, by means of a sliding board partially covering the entrance to the suction pipe. In these two experiments, leakage of air through the stuffing box was prevented by surrounding the stuffing box with water. In experiments No. 3 air was admitted into the suction pipe by opening the valve in an air cock, having an opening $\frac{5}{32}$ inches in diameter, and which was attached to the piezometer on the suction pipe (see Plates III and V). The head producing the flow of air through the air cock was thus approximately equal to the suction head, —2.4 feet of water. Using a coefficient of velocity equal to unity as an extreme case, the velocity of flow of air through the air cock would be equal to about 336 feet per second. Multiplying this velocity by the area of the air cock opening, gives a possible maximum amount of air admitted of about[1] .04 cubic feet per second. The admission of this quantity of air, equal to about 1.6 per cent of volume of water discharged for the case cited, produced, as shown by Table XXIV, a decrease in head pumped against, of about 3.7 feet equivalent to about 20 per cent, and also a decrease in discharge, with head remaining constant, of about 20 per cent. Experiments Nos. 1 and 3, when platted on Plate XII, show respectively a very close agreement with the two discharge curves, speed 1,120 revolutions per minute *entrance to pump under pressure* and *entrance to pump under suction, air leakage, condition No. 1.* The approximate value of the air leakage through the stuffing box, with entrance to pump under suction, may therefore be taken as .04 cubic feet per second when the head pumped against was 15 feet and the speed 1,120 revolutions per minute. The average suction head for these experiments, with this head and speed, was about — 6.0 feet. The leakage through the stuffing box depended on the pressure in the balance chamber, and would only take place when this pressure was less than atmospheric. The pressure in the balance chamber for the speed 1,120 revolutions per minute, (see experimental data, Tables VI and XI) was uniformly about 3.5 feet greater than the suction head, for all heads pumped against. The pressure producing the leakage of air through the stuffing box, with entrance to pump under suction, was thus numerically 3.5 feet less in each case than the suction head. The elevation of the water in the suction pit being fixed, the suction head was least (i. e. numerically greatest) for the low heads pumped against, when the discharge was greatest. The leakage of air was thus greatest for the low heads pumped against, and least for the high heads. For the head of impending delivery, with zero discharge, the suction head was equal to — 2.5 feet, and the pressure in the balance chamber equalled — 2.5 + 3.5 + 1.0 feet (see Table IX, Reference No. 3) and leakage through the stuffing box would not have taken place. The amount of the *air leakage, condition No. 1,* was thus a maximum of about .04 cubic feet per second for the low heads pumped against, and gradually decreased as the head increased and at the head of impending delivery practically equalled zero.

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[1] In order to test this computation of the amount of air admitted, an experiment was subsequently made to determine the rate of inflow through the air cock. An air tight chamber, having a capacity of 1.3 cubic feet, was connected to the six inch suction pipe, and in effect had the nozzle of the air cock projecting into the air tight chamber. The pump was run at the speed of 1120 revolutions per minute and the suction head adjusted to a value of —2.4 feet. On opening the air cock, the pressure in the air chamber was reduced from atmospheric pressure, taken as zero, to —1.0 feet of water, in a time period of one and one-half seconds, and subsequent reduction in pressure followed more slowly. Assuming volume times pressure as constant in the air chamber, the resulting computation shows that the inflow of air during the first time period of one and one-half seconds, was at an average rate of about .027 cubic feet per second.

The amount of the "*Slight air leakage, condition No. 2,*" may be approximately estimated by comparing the curves of discharge with and without air leakage and assuming the air leakage to be proportional to the reduction in discharge. Plate XIII gives the results of experiments with *entrance to pump under suction, air leakage condition No. 2*, while Plate XIV gives the results with *entrance to pump under pressure*. For low heads pumped against, 10–15 feet, the reduction in discharge due to air leakage was about ten per cent, or about one-half the reduction that occurred due to *air leakage, condition No. 1.* The approximate amount of *air leakage, condition No. 2*, may then be taken as about one-half that which occurred under condition No. 1.

The effect of air leakage on efficiency is shown on Plate XII, by a comparison of the curves showing the efficiency, for a certain speed as 1,120 revolutions per minute, under the two conditions *entrance to the pump under pressure* and *entrance to pump under suction, air leakage condition No. 1.* The horse power output being equal to the product of a constant times head pumped against times discharge, the effect of leakage of air for a given head was to reduce the horse power output, in the same proportion that the discharge was reduced. The results of experiments, Plate XII, show that the effect of leakage of air, was also to decrease the horse power input in practically the same proportion that the discharge was decreased, for heads from zero up to about five feet less than the maximum head which the pump held up. Since the efficiency is equal to the ratio of the horse power output to horse power input, and these quantities were reduced in the same proportion, it follows that the efficiency remained the same. For heads equal to and slightly less than the maximum head which the pump held up, the effect of air leakage was to reduce the discharge and horse power output by a larger percentage than the horse power input and the effect was a reduction in efficiency. The results show, therefore, that for the range of heads from zero up to about five feet less than the maximum, the effect of air leakage, in quantity at low heads, not to greatly exceed the limits of the experiments, about .04 cubic feet per second, and gradually decreasing as the head increased, was to leave the efficiency curve the same, while for heads equal to and slightly less than the maximum head which the pump held up, and covering the economical working condi-

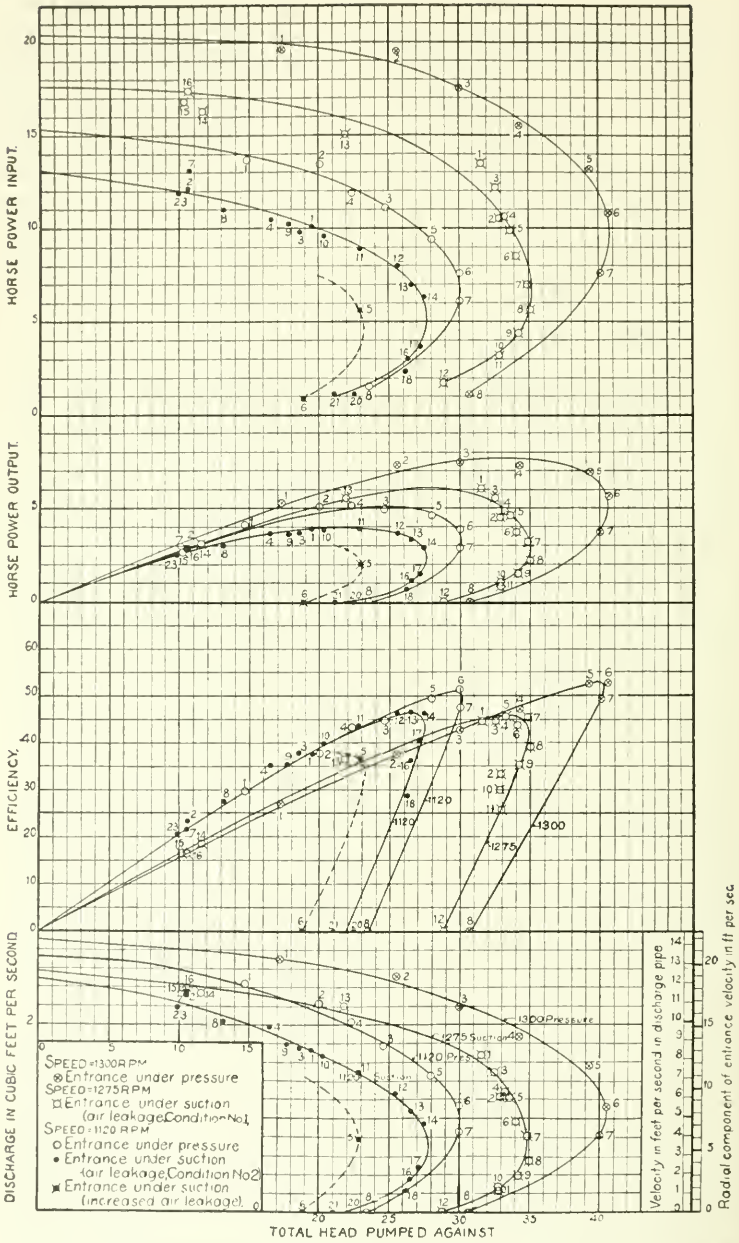

PLATE XII—EXPERIMENTS WITH A 6-INCH HORIZONTAL CENTRIFUGAL PUMP.

Circular Case: Comparison of Results, Entrance to Pump under Pressure and Entrance to Pump under Suction with Air Leakage, Condition No. 1.

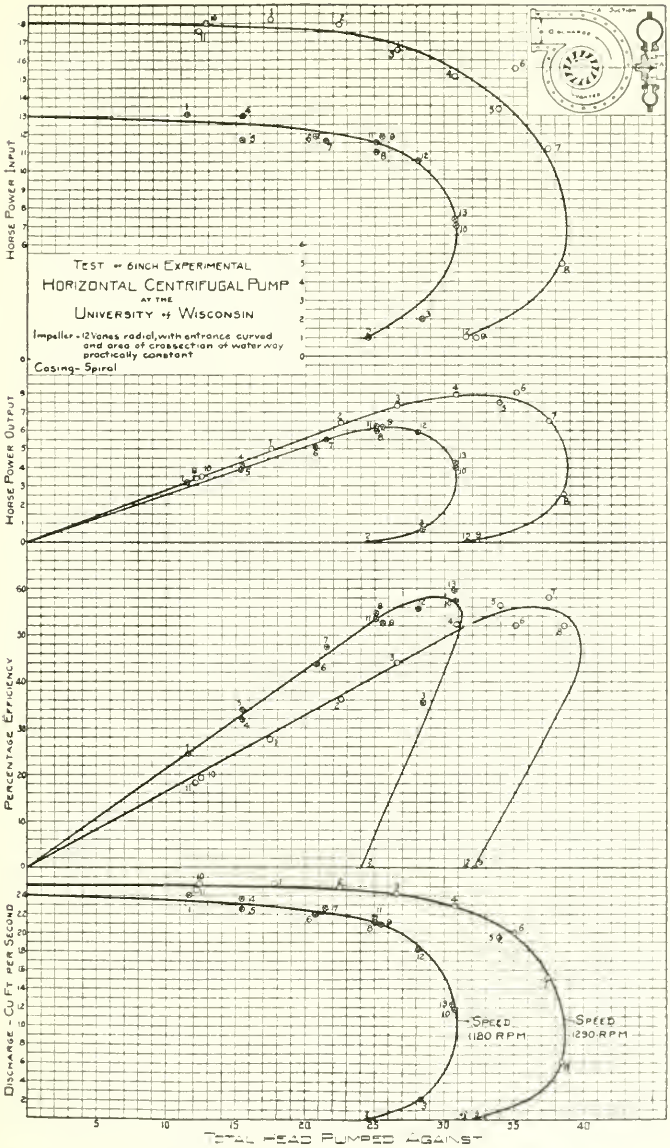

Plate XIII—Experiments with a 6-inch Horizontal Centrifugal Pump.

Spiral Case; Entrance to Pump under Suction, with Slight Air Leakage, Condition No. 2.

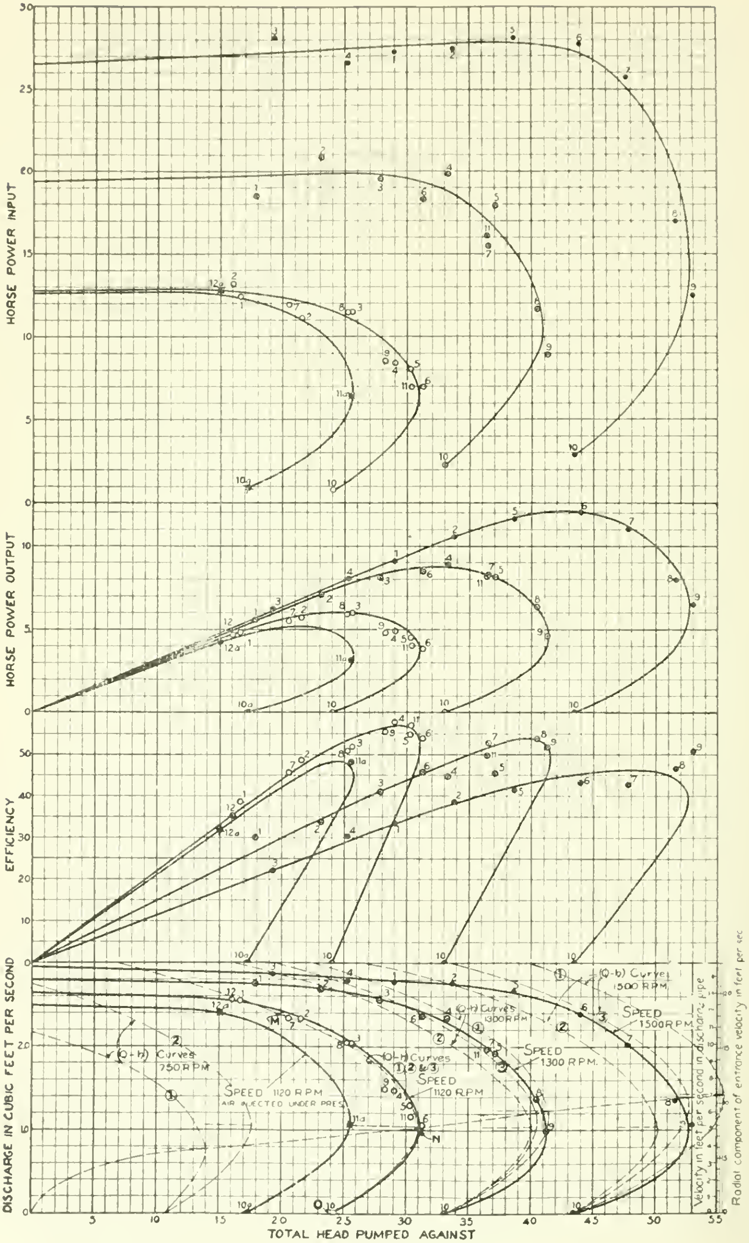

PLATE XIV.—EXPERIMENTS WITH A 6-INCH HORIZONTAL CENTRIFUGAL PUMP.

Spiral Case; Entrance to Pump under Pressure.

tion of the pump, the effect was a reduction and a cutting off of the upper portion of the efficiency curve as shown. For the speed of 1,120 revolutions per minute the reduction in maximum efficiency amounted to about five per cent.

At the condition of most economical working, speed 1,120 revolutions per minute, and head about 29 feet, the suction head, with entrance to pump under suction, was about —3.5 feet. This would give a pressure in the balance chamber of practically zero and there would be no leakage through the stuffing box. The leakage that took place was very slight and must have occurred on the suction side of the pump, and in amount, judging from the rate of collection of air bubbles in the glass tube, (see page 85) did not exceed about one-quarter of that at the lower head of about 15 feet.

The conclusions as to the effect of leakage of air at the economical condition of working, speed 1,120 revolutions per minute, head about 29 feet, are that with an air leakage not to exceed about .01 cubic feet per second, equal to about one per cent of the volume of water discharged, there was a decrease in head of about 10 per cent, a decrease in discharge of about 15 per cent and a decrease in efficiency of about 5 per cent. If the head were maintained constant the effect on discharge would be very much increased, and would be equal to from 20 to 25 per cent.

An air leakage to the amount of .01 cubic feet per second would easily pass unobserved in the ordinary working of a centrifugal pump, while the amount of .04 cubic feet per second, would probably be noticed by a careful observer, by the drawing in of oil through the stuffing box around the pump shaft. A glass tube, placed on the discharge pipe as described, furnishes a practical means for testing for air leakage.

RESULTS OF EXPERIMENTS WITH PUMP HAVING SPIRAL CASE

General Forms of Curves Showing Characteristics of the Pump with Spiral Case. Plate XIV shows the results of experiments with the spiral case, with entrance to pump under pressure, and may be taken as typical of the results with the six inch pump. The discharge was greatest for the low heads pumped against, and gradually decreased in amount as the head increased, until the maximum head which the pump would hold up was reached. From this point both the discharge and head pumped against decreased, until the head of impending delivery was reached when the discharge was zero. It will be seen that the pump delivered water against heads higher than the head of impending delivery, and that a portion of the kinetic energy of the water, in the form of velocity head, was recovered in the form of pressure head, as the water passed through the casing of the pump. The following equation gives the relation between the peripheral velocity, V, and the head of impending delivery, h_i, and was the same for each of the speeds 1,120, 1,300 and 1,500 revolutions per minute:

$$V = 1.09 \sqrt{2 g h_i},$$

or

$$h_i = 0.84 \frac{V^2}{2 g}.$$

When delivery commenced, the heads pumped against gradually increased, and the maximum increase in heads pumped against for the speeds named, were respectively about 30, 26 and 22 per cent of the heads of impending delivery.

The equations giving relations between V and the maximum head, h, pumped against are respectively:

For speed 1,120 R. P. M.......$V = .95 \sqrt{2gh}$ or $h = 1.10 \frac{V^2}{2g}$

For speed 1,300 R. P. M.......$V = .96 \sqrt{2gh}$ or $h = 1.08 \frac{V^2}{2g}$

For speed 1,500 R. P. M.......$V = .98 \sqrt{2gh}$ or $h = 1.04 \frac{V^2}{2g}$

Referring to the *efficiency-head* curve: the efficiency varies almost directly with the head pumped against, until a head corresponding to the maximum efficiency is reached at about ninety-five per cent of the maximum head which the pump will hold up. From the point of maximum efficiency, the curve makes a sharp bend and decreases to zero at a point corresponding to the head of impending delivery. The maximum efficiencies obtained with the spiral casing, for the speeds of 1,120, 1,300 and 1,500 revolutions per minute, were 57, 54 and 47 per cent respectively, and show a gradual decrease as the speed increased.

The equations giving the relation between V, and the head pumped against, which corresponds to the maximum efficiency, are respectively:

For speed 1,120 R. P. M.......$V = .98\sqrt{2gh}$ or $h = 1.04\frac{V^2}{2g}$

For speed 1,300 R. P. M.......$V = .99\sqrt{2gh}$ or $h = 1.02\frac{V^2}{2g}$

For speed 1,500 R. P. M.......$V = 1.00\sqrt{2gh}$ or $h = 0.99\frac{V^2}{2g}$

The head corresponding to the maximum efficiency was thus approximately equal to $\frac{V^2}{2g}$, and was about twenty per cent greater than the head of impending delivery.

The form of the curves showing the relation of horse power input and horse power output to head pumped against, are shown in Plate XIV and do not need further explanation.

Characteristic curve, showing results of experiments with pump having spiral case. From the experimental results at the three speeds 1,120, 1,300 and 1,500 revolutions per minute, Plate XIV, a set of curves, termed a "*Characteristic curve,*" Plate XV, has been drawn as one diagram, on which are shown, by means of rectangular co-ordinates and contour lines, all of the characteristics of the pump at all speeds within the range of the observations.

On this diagram the abscissae represent speed of the pump and the ordinates represent discharge. The numerical values of head pumped against, horse power input, horse-power output and efficiency, are obtained by interpolation between the various contour lines by which they are respectively represented. The diagram was constructed by noting on each of the vertical lines representing the speeds of 1,120, 1,300 and 1,500 revolutions per minute, numerical values of the experimental results as shown by the respective average curves on Plate XIV, and finally adjusting contour lines to the plotted points. For example on Plate XIV, speed 1,120 revolutions per minute, the vertical line representing 25 feet head pumped against, crosses the curve representing discharge at two points, and the numerical values of the discharge served to locate two points on the characteristic diagram through which to draw the curve representing 25 feet head pumped against. Values of the horse power output, horse

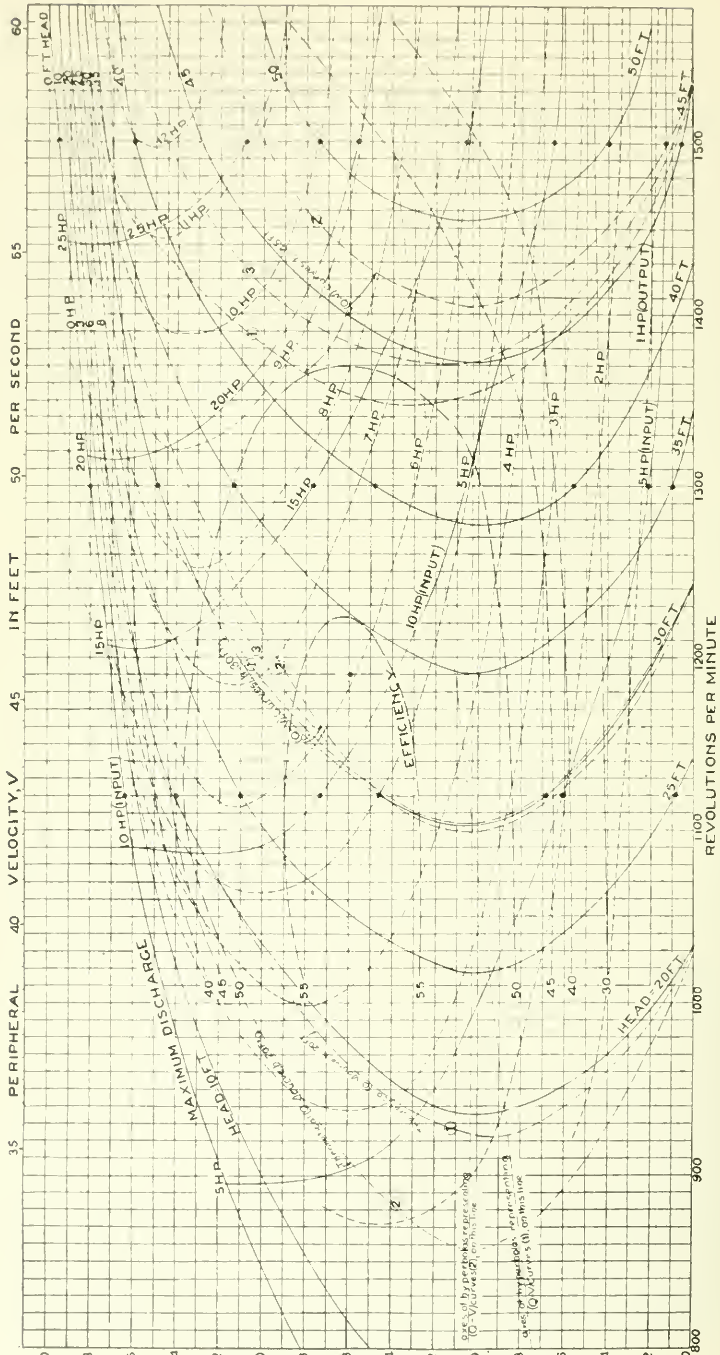

Plate XV—Characteristic Curve, Showing Results of Experiments with Pump Having Spiral Case.

power input and efficiency, corresponding to these discharges and 25 feet head pumped against, were also noted on the diagram. The process was repeated for at least each multiple of five feet of head pumped against, and the entire range of head from zero to the maximum covered. The discharge corresponding to zero head pumped against gave one point for the curve of maximum discharge on the characteristic diagram. The experimental data, as shown by the curves for speeds of 1,300 and 1,500 revolutions per minute, were transferred to the characteristic diagram in a similar manner. Contour lines were finally adjusted to fit the various values noted on the diagram.

Referring to the curve representing 35 feet head, and considering that the pump is to overcome a head of 35 feet between water levels, with the valve in the discharge pipe wide open, the pump will not commence to deliver water until a speed of 1,340 revolutions per minute has been reached. There will then be a rapid increase of discharge, until a balance is reached, when the discharge is 2.3 cubic feet per second. The variation in discharge due to any variation in speed, will then be shown by the curve representing 35 feet head. The diagram thus shows, in a condensed form, all the characteristics of the pump. For example, assuming a fixed head pumped against, and a required increase in discharge, the diagram shows the necessary increase in speed and the resulting change in efficiency and power required. For the above case with a head of 35 feet if the speed of the pump were reduced below the value 1,190 revolutions per minute the delivery of water would cease. The values of the discharge represented by the under part of the curve for speeds greater than 1,190 revolutions per minute could be only obtained by partially closing the valve in the discharge pipe. There was therefore a certain minimum value of the discharge which could be obtained with the valve wide open, and this value, one cubic foot per second for the present case, is seen to have been practically independent of the head and speed.

Results of Experiments With Pump Having Circular Case

The results of the experiments with the circular case are shown on Plate XII, by the curves showing results with *entrance to pump under pressure*. These curves have been discussed slightly, in connection with the experimental results showing the effect in air leakage. It will be noted that the curves are very similar in form to those with the spiral case, and therefore a comparison of the results with the two cases will be sufficient explanation.

Comparison of Results of Experiments With the Spiral Case and Circular Case

In order to show the comparison of the results of the experiments with the two casings, Plate XVI has been arranged. Curves A and B represent respectively the results with the spiral and circular cases at the speed of 1,120 revolutions per minute, while curves C and D represent the results with the spiral and circular cases at the speed of 1,300 revolutions per minute.

Referring to the *efficiency-head* curves; for a speed of 1,120 revolutions per minute, the efficiency curve for the spiral case lies entirely above that for the circular case, the maximum efficiency with the spiral case being about fifty-seven per cent, six per cent greater than the maximum efficiency with the circular case. For the speed of 1,300 revolutions per minute, the difference of the maximum efficiencies is apparently not so great, being about two per cent in favor of the spiral case.

Referring to the *discharge-head* curves; for heads up to about ten feet, the discharge is seen to be slightly greater with the circular case, while for heads between ten feet and the maximum head which the pump will hold up, the discharge for a given head is uniformly about twenty per cent greater with the spiral case. With the speed of the pump at 1,120 revolutions per minute, the spiral case therefore, when working under the most economical condition, capacity about 1.4 cubic feet per second, and head about 30 feet, would furnish about twenty per cent more water than the circular casing and would have about five per cent greater efficiency. The percentage increase in power required for the twenty per cent increase in discharge, would amount to about twelve per cent. For the speed 1,300 revolutions per minute, the comparison is not quite so favorable to the spiral casing, seventeen per cent increase in power being required for the twenty per cent increase in discharge.

If the speed of the pump with the spiral case is reduced from 1,120 to about 1,100 revolutions per minute, the curve showing

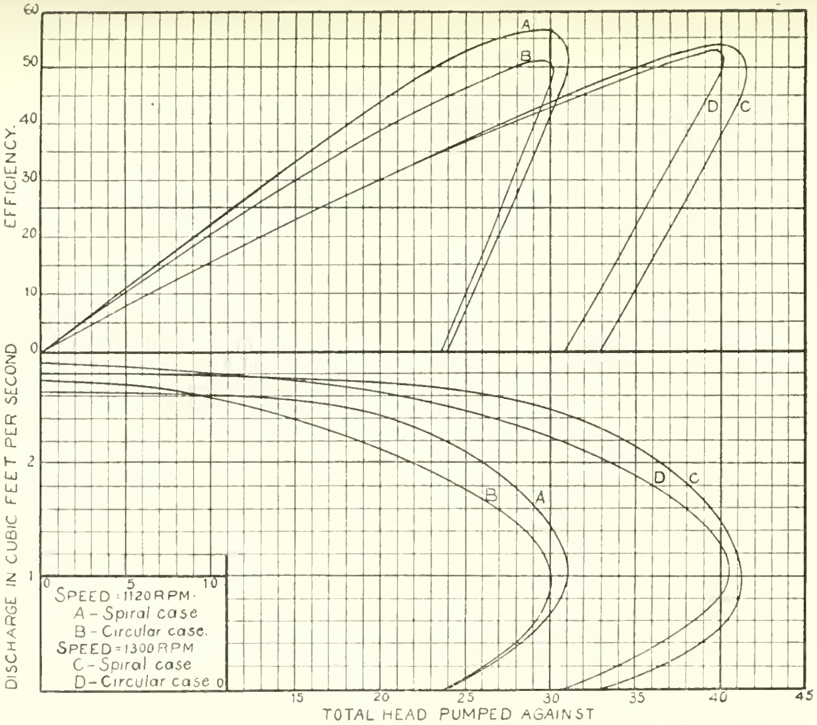

Plate XVI—Experiments with a 6-inch Horizontal Centrifugal Pump.

Comparison of Results of Experiments with Circular Case and Spiral Case.

relation of discharge to head pumped against, would practically coincide with the similar curve for the circular case. speed of 1,120 revolutions per minute, at the condition of economical working, the discharge being about 1.4 cubic feet per second and head pumped against about 28.5 feet. The powers delivered in raising the water through the given head, would then be the same for the two pump cases, and the powers required would be inversely as the efficiencies of the two cases. Using efficiencies of fifty-seven and fifty-two per cent, the pump with the circular case would require about ten per cent more power to pump the same quantity of water against a given head, and the speed would have to be about 20 revolutions per minute greater. At the speed of 1,300 revolutions per minute, the comparison became slightly more favorable to the circular case, the results showing that about four per cent more power was required with the circular case for the same amount of power delivered.

The comparison of the two cases with reference to the relation of the peripheral velocity, V, to the heads of impending delivery, and maximum heads which the pump would hold up, and also the drag of the impeller, is shown by Table XXV.

The table shows that the head of impending delivery is greater with the spiral case than with the circular case, by an amount equal to about $.04 \frac{V^2}{2g}$, or about five per cent of the head of impending delivery. The conclusion to be drawn is that the head of impending delivery, instead of depending entirely on the pressure or centrifugal head $\frac{V^2}{2g}$ developed by the rotation of the water in the impeller, also depends on the rotation of the water in the free vortex surrounding the impeller and decreases as the radius of the free vortex increases.

That the rotation of the water extended beyond the space termed the vortex, and at least partially into the portion of the case termed the discharge chamber, is shown by the readings of the pressure gages, on the center line of the discharge chamber for the condition of impending delivery (see Table XXVI). With the spiral case the cross-section of the discharge chamber gradually increased from a minimum at the point termed the throat, and finally equalled the cross-section of the discharge

TABLE XXV.

EQUATIONS FOR VALUES OF THE HEAD OF IMPENDING DELIVERY AND MAXIMUM HEAD FOR PUMP WITH SPIRAL AND CIRCULAR CASES; ALSO VALUES OF DRAG OF IMPELLER.

Form of case.	Speed R. P. M.	Equation for head of impending delivery, h_1.	Drag of impeller H. P.	Equation for maximum head, h.	Maximum head recovered.
Spiral..............................	1120	$v = 1.09\sqrt{2gh_1}$ or $h_1 = .84\frac{v^2}{2g}$	0.8 (?)	$h = 1.10\frac{v^2}{2g}$	$.26\frac{v^2}{2g}$
"	1300	" "	2.3	$h = 1.08\frac{v^2}{2g}$	$.24\frac{v^2}{2g}$
"	1500	" "	2.9	$h = 1.04\frac{v^2}{2g}$	$.20\frac{v^2}{2g}$
Circular	1120	$v = 1.11\sqrt{2gh_1}$ or $h_1 = .81\frac{v^2}{2g}$	1.5	$h = 1.06\frac{v^2}{2g}$	$.25\frac{v^2}{2g}$
"	1300	$v = 1.12\sqrt{2gh_1}$ or $h_1 = .80\frac{v^2}{2g}$	1.4	$h = 1.05\frac{v^2}{2g}$	$.25\frac{v^3}{2g}$

pipe at the outlet of the pump. The velocity of the water in the discharge chamber therefore decreased approximately as the area of cross-section increased. These variations in velocity would result in variations in pressure. The results of experiments with the spiral case showed that the pressure gradually increased from point No. 1 to point No. 8 of the discharge chamber. With the circular case, the area of cross-section of the discharge chamber being constant, the velocity and pressure at a given radius would be expected to be constant. The experiments, however, show a very slight increase in pressure close to the connection of the discharge chamber to the discharge pipe. Table XXVI is a summary showing the results of the measurements of pressure in the discharge chamber and vortex, for the spiral and circular cases, for the condition of impending delivery. For the spiral case the table shows that the values of the pressure along the center line of the discharge chamber increased from three to six feet, the amount depending on the speed, and gradually approached the value of the discharge head. For the circular case, the pressure in the discharge chamber was practically constant, being about two-tenths feet less than the discharge head. With the circular case, speed 1.120 revolutions per minute, the average pressure in the space termed the vortex was about one foot less than the pressure in the discharge chamber.

The maximum head which the pump would hold up with a given speed, Table XXV, was greater with the spiral case than with the circular case by an amount equal to about $.04 \frac{V^2}{2g}$. As the head of impending delivery was also greater with the spiral case, by this same amount, the head recovered from the condition of impending delivery was therefore practically the same with both cases. The drag of the impeller, Table XXV, was the power required to hold up the head of impending delivery. This power was used to repump the slight leakage, which takes place through the joints at the outlet of the impeller and returns to the suction side of the pump through the balance chamber, and also to overcome the frictional resistance due to the rotation of the impeller and water. With the spiral case a portion of the rotating water in the discharge chamber and vortex is accelerated when it passes the throat and then gradually retarded.

TABLE XXVI.

Results of Measurements of Pressures in Discharge Chamber and Vortex for Condition of Impending Delivery.

Form of case.	Table.	Ref. No.	Speed R. P. M.	Pressures in Discharge Chamber (feet).								Discharge head.
				[1]1	2	3	4	5	6	7	8	
Spiral.......	XV	2	1.136	19.2	20.2	21.2	21.6	21.8	21.9	21.9	22.0	22.0
Spiral	XXI	10	1.307	34.1	36.1	37.5	38.1	38.5	38.6	38.5	38.5	38.6
Spiral......	XXIII	10	1.500	43.0	45.6	47.5	48.3	48.7	48.9	49.1	49.1	49.1
Circular	V	6	1.126	16.0	16.0	16.0	16.0	16.0	16.0	16.1	16.1	16.2
				Pressures in Vortex (feet).								
				[1]1	2′	3′	4′	5′	6′			
Circular.....	V	6	1.120	14.9	14.8	14.6	......	15.1	15.1			16.2

[1] See plate XVII for location of points of measurement (1-8 and 1′-6′).

The power required is seen to have been about one horse power greater with the spiral case than with the circular case.

Comparison of Results of Experiments With Spiral Case, Entrance to Pump Under Pressure and Entrance to Pump Under Suction

In order to determine if any variation in capacity or efficiency occurred, when the condition at the entrance to the pump is changed from one of suction to one of pressure, comparison can readily be made between the results shown on Plates XIII and XIV. In the experiments shown on Plate XIII, entrance to pump under suction, *slight air leakage condition No. 2* existed and reduced the discharge about ten per cent for the low heads pumped against. For the economical working conditions of the pump, however, the effect of air leakage was negligible. The results of the comparison of the two plates for corresponding speeds, show a very close agreement between the curves representing capacity, efficiency, horse power output, and horse power input. The effect then of changing from the condition entrance to pump under suction to entrance to pump under pressure, was simply to increase the absolute values of the pressure at all points in the water passages through the pump by the amount by which the pressure at the entrance to the pump was increased.

Measurement of Pressures and Velocities in Casing of Pump

Circular Case; Hydraulic Gradients showing Pressures in Discharge Chamber and Vortex. The general description of the apparatus, as arranged for the measurement of the pressures at various points of the discharge chamber and vortex, together with the method of using the same, has been given under the description of mercury manometers and water gages, page 19. The numerical values of the pressures at the various points are given in Tables IV–XXIII. Plate XVII represents graphically the results of the measurements for the circular case, for the speed of 1,120 revolutions per minute. The pressures at points Nos. 1–8 and 1′–6′ are platted on a development of a cylindrical surface passing through the points Nos. 1–7, the location of the points Nos. 1′–6′ being determined by projection radially on the cylindrical surface; thus values of 1′ and 1 are platted on the same initial vertical line, and values at 4′ and 5 also appear on a common vertical line. The values platted represent the pressures in feet of water at the various points, the zero of each water gage being at the same elevation as the center of the suction pipe. The hydraulic gradients have been drawn for high, low and medium heads pumped against, and thus show the change in gradient due to change in velocity. Referring to reference No. 2, head pumped against 10.6 feet, it will be observed that the pressure at the inner edge of the vortex was below atmospheric, varying from –3.3 to –12 feet of water, –12 representing the pressure at point No. 6′. In the discharge chamber the pressure was practically constant from point No. 1 to point No. 4, then gradually decreased and was a minimum at point No. 7 where the velocity was a maximum. From this point the pressure gradually increased to the value of the discharge head platted at point No. 9. For low heads pumped against, the pressure at the inner edge of the vortex was uniformly about eight to ten feet less than the pressure on the center line of the discharge chamber.

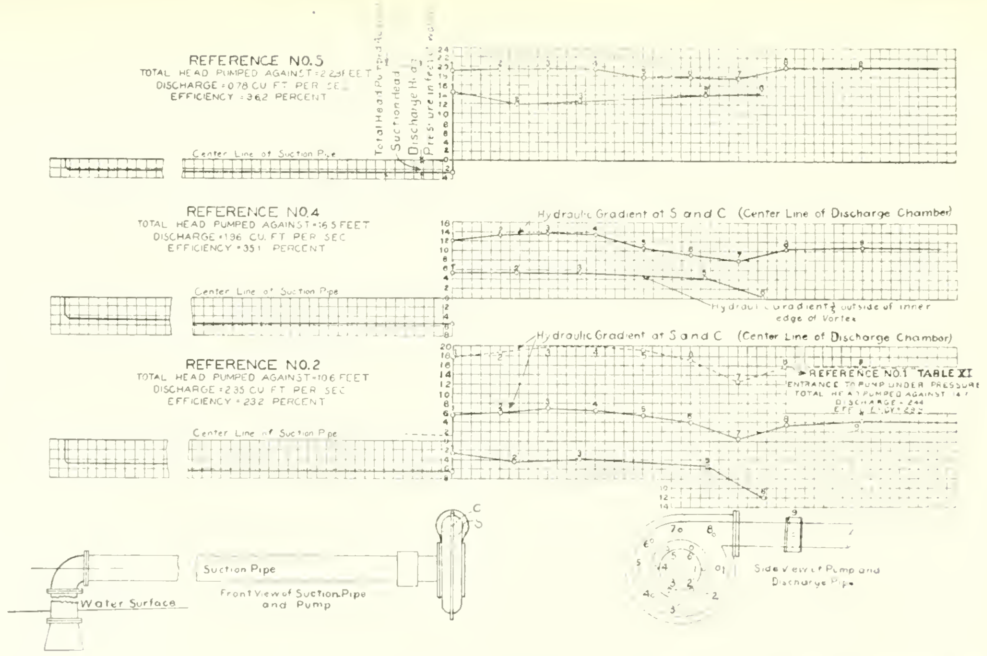

PLATE XVII—DIAGRAM OF HYDRAULIC GRADIENTS FOR CIRCULAR CASE.
Speed 1120 R. P. M., Entrance to Pump under Suction, Data from Table V.
Speed 1120 R. P. M., Entrance to Pump under Pressure, Data from Table XI.

As the head pumped against increased, the difference in pressure between the center line of the discharge chamber and the inner edge of the vortex gradually decreased. For the condition of most economical working, the pressure at the inner edge of the vortex averaged about five feet less than the pressure on the center line of the discharge chamber. This difference represents the amount of head gained due to the vortex, and also to the reduction of velocity when the water passed from the outer edge of the vortex into the discharge chamber. For the condition of impending delivery the revolution of the water in the vortex was maintained only by the friction of the periphery of the impeller, and would therefore be much less than during delivery; the measurements showed a difference in pressure between the inner edge of the vortex and the center line of the discharge chamber of about one foot (See Table XXVI).

For the circular case, speed 1,250 revolutions per minute, the hydraulic gradients are shown on Plate XVIII. The general forms of the curves are very similar to those for the lower speed of 1,120 revolutions per minute. For the condition of economical working, reference No. 3, the amount of head recovered due to the vortex, and reduction of velocity at the outlet of the vortex, amounted to about 8 feet. In order to determine how much of this gain in head should be credited, first to the vortex and second to the reduction of velocity at the outlet of the vortex, a number of measurements of the pressures at the inlet and outlet of the vortex were made and are shown on Plate XXI. For the conditions of speed and discharge shown on the plate, the pressures on the center line of the discharge chamber, at S and C, are seen to have been from one to three feet greater than the pressure at O, the outlet of the vortex. The gain in pressure from the inner edge of the vortex to the outer edge was about 8½ feet. The gain of head in the vortex thus amounted to about four-fifths of the total gain from the inner edge of the vortex to the center line of the discharge chamber. The pressures along the outer edge of the discharge chamber were as shown by the dotted line through point 6a.

Spiral Case: Hydraulic Gradients showing pressures in dis-

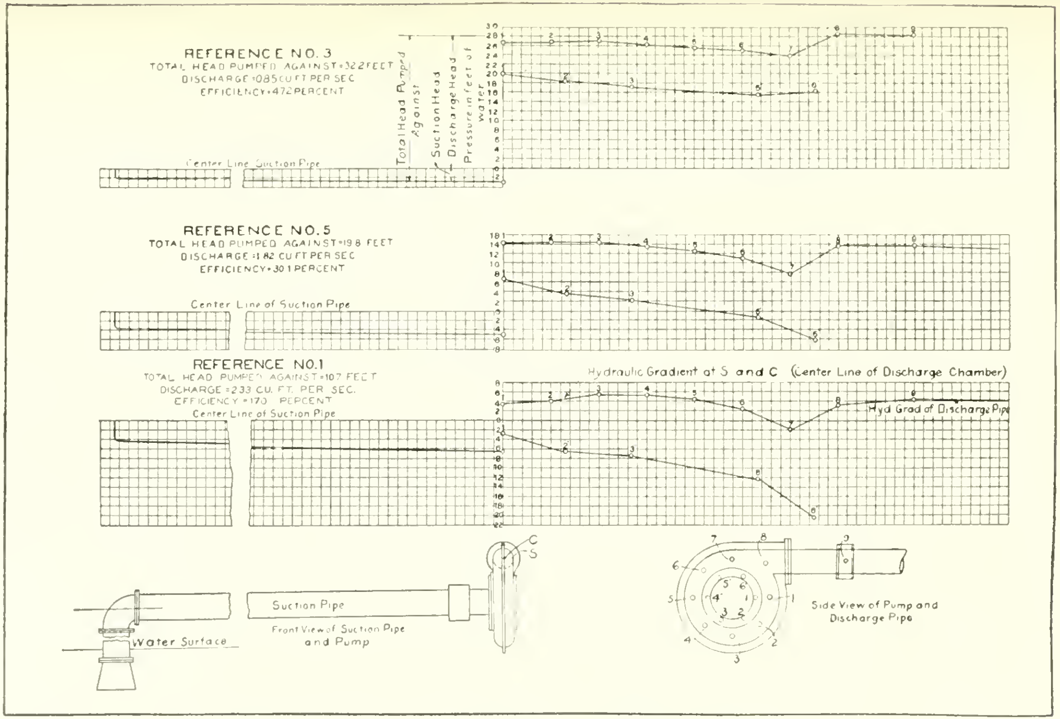

PLATE XVIII—DIAGRAM OF HYDRAULIC GRADIENTS IN CIRCULAR CASE.
Speed 1250 R. P. M., Entrance to Pump under Suction Data from Table IX.

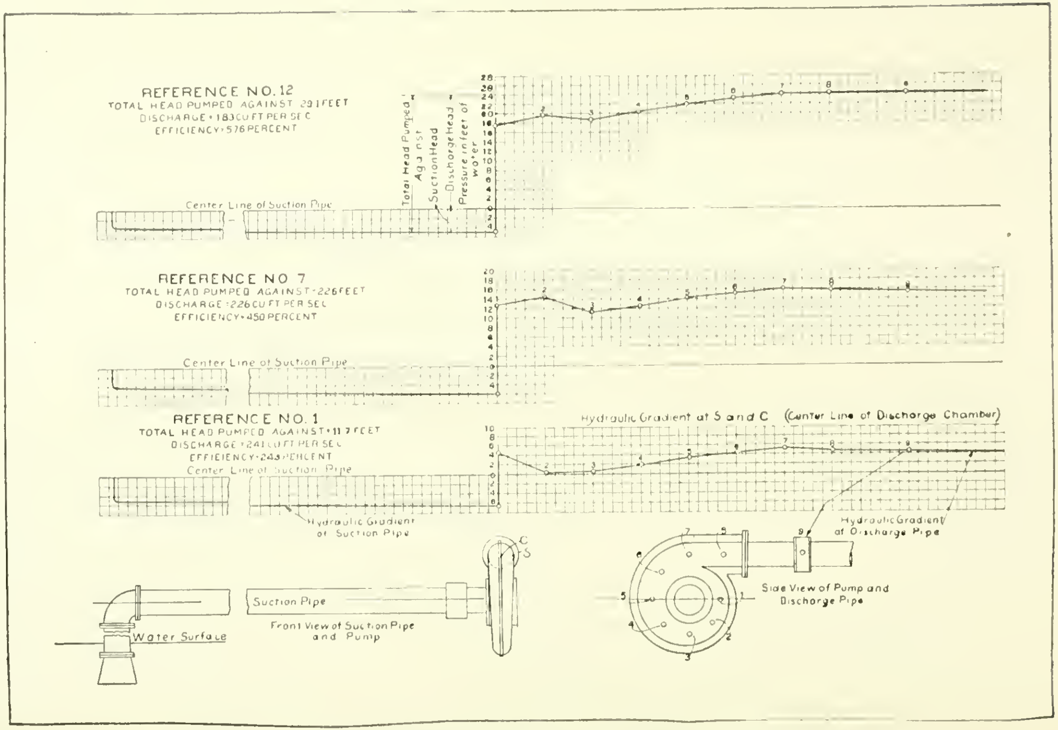

Plate XIX—Diagram of Hydraulic Gradients for Spiral Case.
Speed 1120 R. P. M., Entrance to Pump under Suction, Data from Table XV.

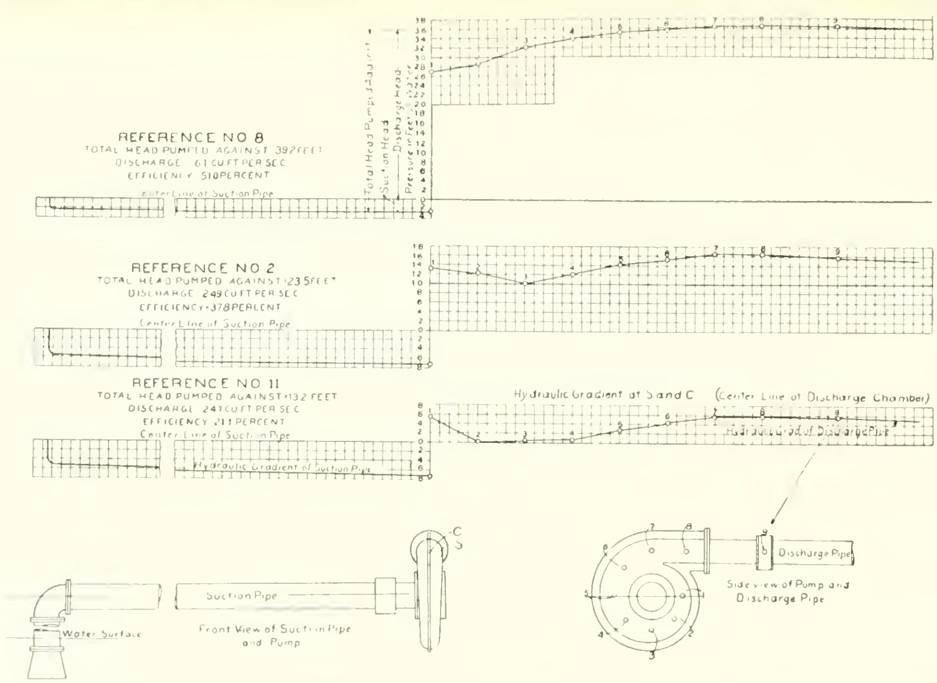

Plate XX—Diagram of Hydraulic Gradients for Spiral Case.
Speed 1290 R. P. M., Entrance to Pump under Suction, Data from Table XVII.

charge chamber. Plates XIX and XX show the results of measurements of pressures, along the center line of the discharge chamber, for the spiral case speeds 1,120 and 1,290 respectively. The pressures on the inner edge of the vortex were not measured. For low heads and large discharge, the pressure on the center line of the discharge chamber was a minimum at points Nos. 2 and 3, and then gradually increased to the value of the discharge head at point No. 9. For the high heads and economical condition of working, the minimum pressure was at point No. 1 and gradually increased to the value of the discharge head at point No. 9.

Circular Case; Measurement of Velocities by means of Pitot Tube. In order to further analyze the gain of head resulting from the reduction of velocity when the water entered the discharge chamber, and also to determine the loss of head resulting from the gradual enlargement of the cross-section, where the discharge chamber joins the discharge pipe, measurements of the velocities were made at points Nos. 1–8 on the center line of the discharge chamber. The velocities were measured by means of a simple form of pitot tube, shown in the photograph Plate XXII, A, and details, Plate XXIII. The pitot tube was made from a copper tube about one-tenth inches inside diameter, the opening to the tube being beveled on the outside so as to make a moderately sharp edge. The tube could be inserted in the discharge chamber, at points Nos. 1–8, through one-quarter inch iron tees, which were attached to the pump casing at these points, by means of one-quarter inch iron nipples. The pressure head was obtained by the readings of the water gages connected to the discharge chamber at these points by rubber tubes (see Plate VI). In order to determine if the pressure head was constant throughout the diametrical section, a form of pressure tube shown by photograph Plate XXII, B, was inserted in the discharge chamber at S, with the sharp end pointing up stream, and the readings of the pressures throughout the width of the discharge chamber, compared with the readings of pressures obtained at the surface of the chamber at S by means of the water gages. The comparisons showed that the pressures were constant throughout the diametrical section, and that readings of pressures at S by means of the

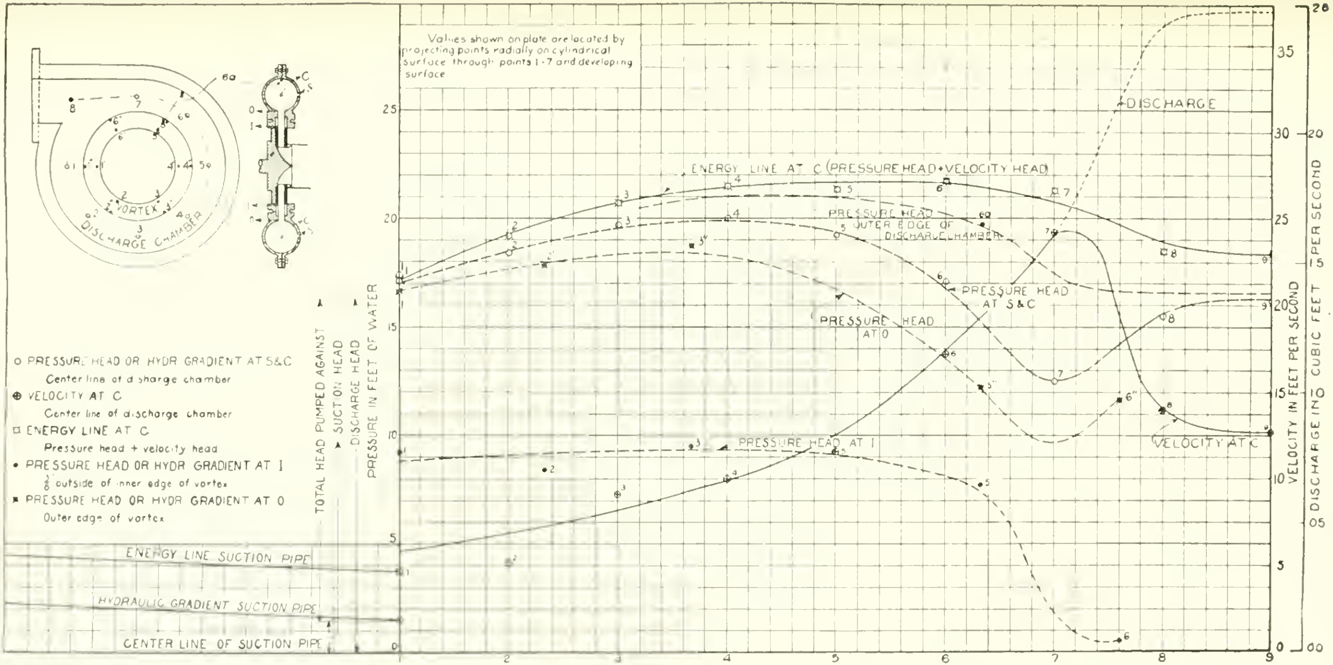

PLATE XXI—DIAGRAM OF PRESSURES AND VELOCITIES IN CIRCULAR PUMP CASE.

Speed of Pump 1120 R. P. M., Discharge 2.44 Cubic Feet per Second, Efficiency about 30 per cent.

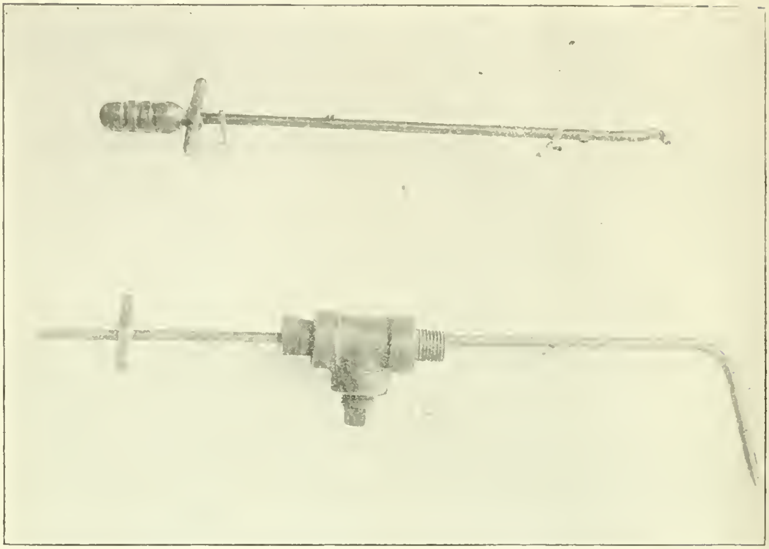

Plate XXII—View Showing Forms of Pitot Tube and Pressure Tube.

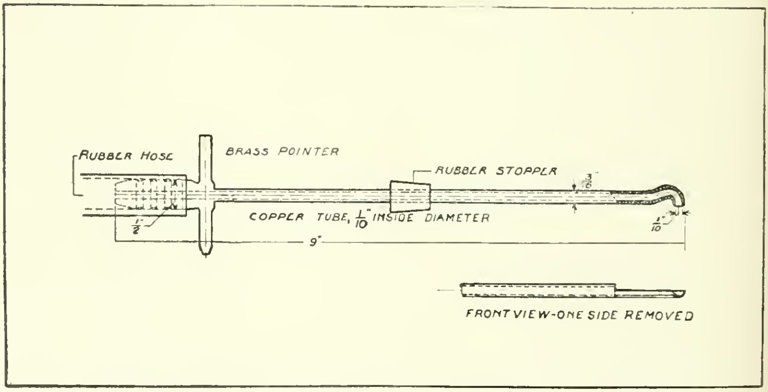
RUBBER HOSE
BRASS POINTER
RUBBER STOPPER
3/16"
COPPER TUBE, 1/10" INSIDE DIAMETER
1/2"
1/10"
9"
FRONT VIEW-ONE SIDE REMOVED

Plate XXIII—Details of Pitot Tube.

water gages, indicated correct values. The length of the portion of the pressure tube pointing upstream was two and one-half inches, and the pressure was transmitted through four holes, each one thirty-second of an inch in diameter, located as shown in the photograph.

The pitot tube was calibrated by being inserted in the jet from a standard sharp edge circular orifice, 0.07 feet in diameter, which was placed in a vertical plane in a suitable pressure chamber. The tube was inserted in the jet at a distance of about one and one-half diameters from the plane of the orifice, and was therefore at a point where the stream lines were parallel and atmospheric pressure existed throughout the cross-section of the stream. It has recently been shown by experiment[1], that the coefficient of velocity for such an orifice is equal to unity, within a small fraction of one per cent, in place of about 0.98 as ordinarily used. The coefficient for the pitot tube has been taken as the ratio of the measured velocity head in the jet to the hydrostatic head on the orifice, and with the coefficient of velocity equal to unity, would express the ratio of the velocity head as measured by the tube, to the actual velocity head.

Table XXVII following, shows the results of the calibration of the pitot tube:

The results of the calibration showed that the coefficient of the pitot tube was equal to unity, within a fraction of one per cent, and that the measured velocity heads equalled the true velocity heads. That the average coefficient for the tube was slightly greater than unity, must have resulted from a slight error in the determination of the reading corresponding to the center of the orifice, on one of the mercury or water gages. The results also show that turning the axis of the tube to an angle of ten degrees with the axis of the jet, made practically no difference in the coefficient, while turning the tube to an angle of 20 degrees decreased the coefficient only about two per cent. This result of allowing the axis of the tube to make a considerable angle with the axis of the jet, and still to give

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[1] Results of experiments at the University of Ohio by Horace Judd & R. S. King, *Engineering News*, Sept. 27, 1906.

TABLE XXVII.

RESULTS OF THE CALIBRATION OF PITOT TUBE, IN JET FROM STANDARD ORIFICE.

Head on orifice. Ft 1	Velocity head by pitot tube. Ft. 2	Coefficient. $\frac{\text{Col. No. 2.}}{\text{Col. No. 1.}}$ 3	Angle of tube with axis of jet degrees. 4
30.58	30.44	.995	0
24.29	24.19	.995	0
20.60	20.65	1.007	0
12.57	13.58	1.000	9
8.91	8.97	1.007	0
7.16	7.18	1.002	0
3.27	3.29	1.006	0
2.17	2.18	1.005	0
.91	0.82	1.010	0
3.42	3.34	0.976	0
3.42	3.41	0.997	20
3.42	3.42	1.000	10
23.99	23 99	1.000	0
24.03	24.11	1.003	10
24.03	23.79	0.989	20
24.07	22.86	0.949	30
[1]30.87	30.73	0.994	0
[1]12.04	12.10	1.002	0
[1]3.70	3.65	.985	0

[1] Experiments made subsequent to using pitot tube in centrifugal pump, as a result of which the tube opening had become slightly damaged.

practically correct results was somewhat unexpected, as experimenters have commonly stated that the plane of the opening in the tube must be at right angles to the axis of the stream. It is probable that the size of the opening has considerable influence on the allowable angular variation in direction for a required accuracy.

Table XXVIII is a summary sheet, giving the results of the measurements with the pitot tube at points Nos. 1–8, on the center line of the discharge chamber. The values in the columns *pressure head plus velocity head* are the results from pitot tube readings, the actual readings being made by a mercury manometer and reduced to feet. The velocity was obtained by subtracting the *pressure head* from the *pressure head plus velocity head*, and substituting the resulting *velocity head* for h in the general formula $v = \sqrt{2gh}$. The general results of the table have been platted on Plate XXI. The velocity on the center line of the discharge chamber, it is seen, increases

TABLE XXVIII.

SUMMARY SHEET; RESULTS OF EXPERIMENTS FOR DETERMINATION OF PRESSURES AND VELOCITIES IN DISCHARGE CHAMBER OF CIRCULAR CASE.

Speed 1,120 R. P. M. April 9, 1908.

Discharged.	Discharge head.	Suction head (pressure).	Total head pumped against.	Insertion of pitot tube.	LOCATION OF PITOT TUBE.															
					1				2				3				4			
					Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.
Cubic ft. sec.	Ft.	Ft.	Ft.	Inches.		Ft.	Ft.			Ft.	Ft.			Ft.	Ft.			Ft.	Ft.	
2.47	16.2	1.5	14.7	Out.	....	17.4	17.4	....	....	18.4	18.4	....	.....	19.7	19.7	....	....	20.0	20.0	....
				0.4	....	....	....	....	....	....	....	....	−110	....	20.9	8.8	−90	....	21.4	9.5
				0.9	[1]180	....	17.7	4.4	0	....	18.4	0.0	−110	....	19.8	0.8	0	....	20.9	7.6
				1.3	....	....	17.4	—	....	....	....	....	.....	....	....	....	....	....	....	....
				1.7	0	....	17.4	—	+45	....	19.2	5.1	+45	....	20.7	8.0	+15	....	21.5	9.8
				2.6	0	....	17.4	—	+45	....	19.2	5.1	+45	....	22.1	12.4	+20	....	22.5	12.7
				3.0	....	....	....	....	....	....	....	....	+45	....	20.7	8.0	....	....	....	....
				3.5	0	....	17.4	—	0	....	18.4	0.0	−110	....	20.7	8.0	+15	....	21.9	11.1

Insertion of pitot tube.	LOCATION OF PITOT TUBE.															
	5				6				7				8			
	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.	Angle of current (degrees).	Pressure head.	Pressure head plus velocity head.	Velocity in feet per second.
Inches.		Ft.	Ft.			Ft.	Ft.			Ft.	Ft.			Ft.	Ft.	
Out.	....	19.2	19.2	....	....	17.1	17.1	....	....	12.5	12.5	....	....	15.5	15.5	....
0.4	00	....	22.6	14.8	0	....	23.6	20.4	0	....	23.9	27.1	0	....	20.1	17.2
0.9	00	....	22.6	14.8	0	....	22.7	19.0	0	....	22.7	25.6	0	....	20.9	18.7
1.3	....	....	....	....	0	....	21.4	16.7	....	....	....	....	....	....	....	....
1.7	00	....	21.3	11.6	0	....	21.7	17.2	0	....	21.6	24.2	0	....	18.5	13.9
2.6	00	....	21.8	12.9	0	....	23.4	20.2	0	....	21.8	24.5	0	....	16.5	8.0
3.0	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
3.5	00	....	22.1	11.1	....	....	23.5	20.3	0	....	22.7	25.9	0	....	18.9	14.8

---

[1] The angle of the current recorded is the angle which the direction of the current makes with the tangent to the center line of the discharge chamber, at the point of measurement of pressure head plus velocity head, zero degrees representing the tangent and normal direction of flow, while signs (+) and (−) represent clockwise and counter-clockwise directions respectively.

from about 5 feet per second at point No. 1, to a maximum of about 24 feet per second at point No. 7.

The values of *pressure head plus velocity head,* express energy per unit weight, in feet of water. These values corresponding to points Nos. 1–8, on the center line of the discharge chamber, have been platted on Plate XXI and termed "*Energy line at C.*" The drop in the energy line from about 21 feet at point No. 7, to about 18.3 feet at point No. 9, shows the loss of head 2.7 feet, due to the gradual enlargement of cross-section and mingling of currents between points Nos. 7 and 8.

The curve representing discharge, taken as the quantity of flow in the discharge chamber, coincides with the curve representing velocity up to point No. 7, from which point it diverges as the cross-section of the discharge chamber increases. This curve shows that nearly one-half of the total discharge entered the collecting or discharge chamber between points Nos. 6 and 8. The conclusion to be drawn from this curve, together with the pressure curves in the vortex chamber, is that the flow through the impeller and vortex was very irregular, and that the larger percentage took place at and near the outlet of the discharge chamber. Also, that the flow through the water passages of the impeller was accelerated and retarded as the periphery of the impeller passed the points of varying pressure in the vortex. It should be stated that the discharge for the case cited above was nearly double that corresponding to the condition of economical working, and shows the variations of pressure and velocity that occurred under rather extreme conditions of crowding. The efficiency of the vortex, however, as will be shown, was greater under these conditions of crowding than when the pump as a whole was working most efficiently.

EFFICIENCY OF THE VORTEX CHAMBER SURROUNDING THE IMPELLER

Radial Outward Flow. When radial outward flow takes place from a central point of supply between two horizontal plates, and the concentric cylindrical sections are maintained full, it follows that the radial velocity at any point will vary inversely as the radius of the point. Neglecting loss of head due to friction and considering the flow steady, it is evident that for any point in the horizontal plane midway between the plates, pressure head plus velocity head is equal to a constant.

Letting r, u and p represent, respectively the radius, velocity and pressure, at the point of supply, corresponding in later discussion to the periphery of the impeller of a pump, and r_n, u_n and p_n, the radius, velocity and pressure corresponding to the radius r_n, and expressing pressures in linear units of water,

$$p_n + \frac{u_n^2}{2g} = p + \frac{u^2}{2g} = C.$$

The numerical increase in pressure, due to increase in radius, would therefore be equal to the difference in velocity heads corresponding to the velocities at the two radii considered, or

$$p_n - p = \frac{u^2}{2g} - \frac{u_n^2}{2g},$$

$$p_n = C - \frac{u^2}{2g}\frac{r^2}{r_n^2}.$$

This is the equation of an hyperbola referred to rectangular coordinates with the center of co-ordinates at the center of the source of supply (center of impeller). The curve is asymtotic to the vertical axis through the center of the source of supply, and to a horizontal line located at height, C, above the center of the plates. Since p_n represents the pressure at radius r_n, it will also represent the height of the free surface of zero pressure, above the horizontal axis midway between the plates and the equation of the hyperbola given, determines therefore, the form of the free surface of zero pressure, and of surfaces of equal pressure.

Free Circular or Cylindrical Vortex. A free circular or cylindrical vortex is a revolving mass of water in which the stream lines are concentric circles and in which, neglecting viscosity, the energy per unit mass is everywhere the same. The total head for each stream line is therefore constant, and on any horizontal plane the pressure head plus velocity head would remain constant. As the only external force consists of balanced normal pressure toward the center of rotation, the angular impulse is zero and hence if, by any slow motion, portions of water should move from one stream line to another, as would occur with a small escape or supply at the center of rotation, their angular momentum would remain constant, and since angular momentum is proportional to velocity times lever arm, the velocity would vary inversely as the radius. The form of the free surface of zero pressure, and of surfaces of equal pressure, would therefore be the same as that for the case of radial outward flow already described.

Free Spiral Vortex. A free spiral vortex is compounded from the motions of a free radial flow and free circular vortex, provided each component of velocity varies inversely as the radius. The actual velocity at any point would therefore be inversely as the radius of the point and the stream lines would form a series of equiangular or logarithmic spirals.

When water is delivered from the circumference of the impeller of a centrifugal pump and suitable opportunity is afforded, a free vortex is formed following somewhat the law of the equiangular outward flow spiral vortex. It is of value to know how nearly the theoretical laws of the spiral vortex are followed.

Plate XXI shows the results of measurements of pressures, in feet of water, in the vortex chamber at the inner edge I and outer edge O, corresponding to a speed of 1,120 revolutions per minute and a discharge of 2.48 cubic feet per second. The actual increase of pressure in feet of water is seen to amount to about 8.5 feet. To determine the increase in pressure or head that would occur if the law of the equiangular spiral vortex is followed: The vanes of the impeller are radial and the tangential component of the absolute velocity, v, at the outlet of the impeller will be taken as equal to the peripheral velocity, V, of the impeller, or to 42.8 feet per second; the radial component of the absolute velocity will be taken as equal to the discharge divided by the area[1] (0.124 square feet) of the outlet openings of the impeller, or 20.0 feet per second. The absolute velocity at the outlet of the impeller, computed from the two components of the velocity, is found to equal 47.3 feet per second. The ratio of the inner radius of the vortex to the outer radius is equal to 0.68 and if the law of the equiangular spiral vortex is followed, the velocity at the outer edge of the vortex would be equal to 0.68 v. The theoretical increase of head would therefore be:—

---

[1] Notice that the area of the outlet openings of the impeller is only about one-half the circumferential area of the impeller. See Part I, page 464.

$$\frac{r^2}{2\,g} - \frac{(68\,r)^2}{2\,g} = 0.54\,\frac{r^2}{2\,g} = 18.8 \text{ feet.}$$

The efficiency of the vortex may be taken as the ratio of the actual head gained to the theoretical head gained; giving an efficiency for the case cited of about 45 per cent. For a discharge corresponding to the economical condition of working, and the same speed, the radial component of the absolute velocity at the outlet of the impeller would be equal to about 10 feet per second. The absolute velocity at the outlet of the impeller would then be equal to about 44 feet per second. The theoretical head gained, due to the vortex chamber, would be equal to about 16.2 feet. The measured gain of head from the inner edge of the vortex to the center line of the discharge chamber (Plate XVII), averaged about 5 feet. Crediting about one-fifth of this amount to the gain of head due to reduction of velocity as the water enters the discharge chamber, there remains about 4 feet as the gain of head due to the vortex chamber. The efficiency of the vortex chamber, at the economical condition of working the pump, was therefore about 25 per cent. For a further decrease of discharge, the actual gain of head from the inner edge of the vortex to the center line of the discharge chamber gradually approached a value of about one foot, which corresponded to the condition of impending delivery (see Table XXVI). The theoretical gain of head for small discharges would remain about 16 feet. The results show, therefore, that the efficiency of the vortex increased with the discharge, and reached a maximum of about 45 per cent.

In order to gain some knowledge of the direction and character of the current in the vortex chamber, an attempt was made to insert a light brass vane of the same width as the vortex, and arranged so as to be free to assume the direction of the current. The vane was about two inches long and was free to turn on a light steel shaft about three-sixteenths inches in diameter, inserted at point No. 4′, Plate VII. One end of the shaft extended through the pump casing and had an index arm attached, for indicating the direction of the vane. On attempting to use the apparatus, it was found to vibrate through an angle of about five degrees, and at such a rapid rate that the steel shaft was repeatedly broken in about one hour's time. The only reliable readings taken were for a discharge and head corresponding practically to results platted in Plate XXI, and indicated that the vane made an angle of about 85 degrees with the direction of the radius through point No. 4′. Very little can be inferred from this reading, however, as to the direction of the current at point No. 4′, as the pressure of the current near the free end of the vane would have greater effect in fixing the direction of the vane, than that near the axis of rotation. As an approximation, the vane may be assumed as parallel to the current at a point about two-thirds the length of the vane from the fixed end; then with an angle of 85 degrees at point No. 4′, the current would be making an angle of about 70 degrees with the radius through the point two-thirds the length of the vane from the fixed end, and located about midway in the vortex chamber.

The very rapid vibration of the vane indicated that the currents went through the vortex chamber in a manner which may be likened, somewhat, to the flow of the jets from a simple form of barker wheel, constructed by having the outlets submerged, and located on the circumference of the lower end of a vertical cylinder filled with water, and made to revolve by the relief of pressure due to the flow through the outlets. The vane in the vortex chamber apparently changed its direction as each stream or jet from the twelve water passages in the impeller of the pump passed by it. As the speed of the pump was 1,120 revolutions per minute, the indications were, though not definitely proven, that the rate of vibration of the vane was about 13,000 per minute.

RESULTS OF MEASUREMENTS SHOWING ROTATION OF WATER IN THE SUCTION PIPE, NEAR THE ENTRANCE TO THE PUMP.

In order to gain experimental knowledge in regard to the conditions that existed at the entrance to the impeller of the pump, an instrument shown by photograph, Plate XXIV, and which has been termed a rotometer, was devised. The instrument consists of four plain blades of light galvanized iron, arranged to intersect and revolve about an axis located on the center line of a piece of brass pipe about six inches long and six inches in diameter. The blades were 5 inches long in the direction of the diameter of the pipe, and had a width of 2½ inches, measured along the axis of the pipe. The instrument could be inserted in a common six inch iron pipe, and if the water had a spiral motion in passing through the pipe, the blades of the instrument would be rotated. The speed of rotation of the blades would be slightly less than that of the water, but the results would be approximate and at least show whether spiral motion of the water existed. A make and break electrical circuit was arranged on the instrument, somewhat similar to that on the ordinary water current meter, and the number of revolutions in a given time period was obtained by an electrical recorder placed in the circuit.

The rotometer was placed in the six-inch suction pipe and readings were taken with the center of the blades in three positions, 4, 6 and 18 inches from the entrance to the impeller, the results being shown in Table XXIX.

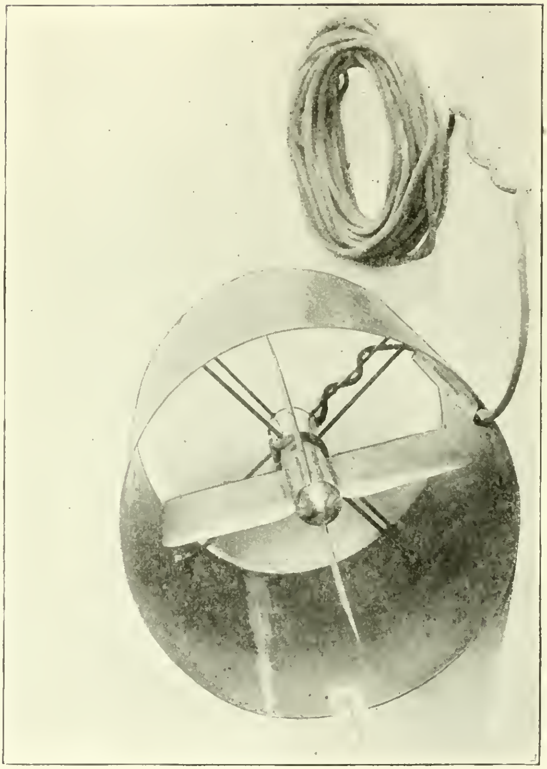

Plate XXIV—View Showing Rotometer Used for Determining Approximate Rate of Rotation of Water in Suction Pipe.

TABLE XXIX.

Results of Experiments with Rotometer in Suction Pipe.

Circular Case; Impeller With 12 Vanes, Area of Water Way Practically Constant; Center of Blades of Rotometer Four, Six and Eighteen Inches form the Entrance to Impeller

Speed of pump.	Head pumped against.	Discharge.	Longitudinal velocity in suction pipe.	Reading of Rotometer. Location			Computed circumferential velocity. (6 in. diameter.)
				4"	6"	18"	
R. P. M.	Ft.	Cubic ft. per sec.	Ft. per sec.	R. P. M.	R. P. M.	R. P. M.	Ft. per sec.
977	14.1	2.00	10.0	....	39	....	1.02
1,124	17.5	2.28	11.4	....	40	....	1.05
1,128	24.0	1.85	9.2	....	29	....	0.76
1,130	29.2	1.28	6.4	....	20	....	0.52
1,125	30.2	[1]1.00	5.0	....	16	....	0.42
1,130	29.8	0.90	4.5	....	11	....	0.29
1,145	29.4	0.70	3.5	....	50	....	1.30
1,115	[2]23.1	0.00	0.0	....	233	....	6.10
1,307	[2]31.1	0.00	0.0	....	276	....	7.20
1,050	16.0	2.20	....	25	....	....	....
1,200	18.0	2.50	....	30	....	....	....
1,400	20.0	2.80	....	30	....	....	....
1,120	[2]23.0	0.00	....	287	....	....	....
1,068	17.2	2.25	....	....	....	16	....
1,138	17.9	2.40	....	....	....	25	....
1,156	[2]24.5	0.00	....	....	....	242	....

[1] Discharge coresponding to maximum efficiency.
[2] Discharge valve closed.

The results of Table XXIX show that as a result of the viscosity of the water, and of the rotation of the curved brass guide which was keyed to the end of the pump shaft, and which served to gradually change the direction of the water entering the impeller through an angle of 90 degrees, or from a combination of the above, and a natural tendency of the water to enter the impeller in a direction having a component in the direction of rotation of the impeller, a spiral vortex of some form was set up in the suction pipe. Referring to the readings taken six inches from the entrance to the pump, it will be seen that the blades revolved at the rate of about 40 revolutions per minute for the large discharge and low head, and then decreased as the discharge decreased, and was a minimum of about 11 revolutions per minute, corresponding to a discharge just below the economical working conditions of the pump. For a further decrease in discharge, with decrease in head, the rotation rapidly increased and reached a value of about 233 revolutions per minute, corresponding to zero discharge. The vortex then occupied the whole diameter of the suction pipe and extended a considerable distance upstream in the pipe, as shown by rate of rotation at eighteen inches from the impeller, being practically the same as at six inches. That the rate of rotation of the water was fastest at the center of the pipe, was shown by the following readings: For a speed of 1.300 revolutions per minute, entrance to pump under pressure, the elevation of the water in the glass tube, which was connected to the suction piezometer and showed the suction head (positive), was 0.3 feet greater than the elevation of the water in the suction pit, while if the computed circumferential velocity of 7.2 feet per second had occurred, the water in the tube would have been at an elevation $\frac{V^2}{2g}$ or about 0.8 feet greater than that in the suction pit.

The comparison of the readings for distances of four inches and six inches from the entrance to the pump for the large discharge, seems to show that a slight increase in the rate of rotation of the blades occurred with increase of distance from pump. This result may have been caused by the blades of the rotometer, extending into the stream lines near the edge of the pipe, and which had a much smaller rate of rotation, and would imply that the diameter of the spiral vortex, for a short distance at least, increased with distance from the pump. The readings at the distance of eighteen inches show that for the large discharges, the rotation extended upstream in the pipe a distance of about two or three feet.

The results with the rotometer, in general, show that a spiral motion was formed in the suction pipe, as the water approached the impeller, and that the absolute velocity of the water at entrance to the impeller, even at the economical working condition of the pump, had a component in the direction of rotation of the impeller. It would be of value to know if the spiral motion in the suction pipe still persisted, were the water to be guided at entrance to the impeller by stationary in place of a revolving curved guide.

EQUATION REPRESENTING APPROXIMATE LAW FOR THE DISCHARGE OF A CENTRIFUGAL PUMP

An attempt has been made to determine the approximate law showing the relation between the discharge Q, the head h, pumped against and the peripheral velocity V, of the impeller. For this purpose two general equations

$$K_1 Q^2 - K_2 Q V - V^2 + K_3 h = 0, \qquad (1)$$

and

$$A Q^2 - B Q - V^2 + Ch = 0 \qquad (2)$$

have been assumed, where K_1, K_2, K_3 and A, B and C are constants to be determined. These two forms of equations would naturally be suggested, as possibly representing the relation of the three variables Q, V and h, after platting the experimental results.

EVALUATION OF COEFFICIENTS FOR GENERAL EQUATION NO. 1

The form ot equation $K_1 Q^2 - K_2 Q V - V^2 + K_3 h = 0$ has been derived by Mr. Charles H. Innes[1] and Mr. Egon R. Grünebaum, by following the ordinary theory of the centrifugal pump, and equating the theoretical head to the head pumped against, plus the head lost. The final equation, when reduced, takes a form similar to the one assumed. The theoretical head developed, and head lost, probably occur somewhat as assumed and the formula thus has a rational basis.

The equation contains three variables Q, V and h, and represents the surface of the somewhat complicated hyperbolic paraboloid; but by taking each of the variables consecutively as constant, the equations between the two remaining variables represent simple curves, two parabolas and one hyperbola. With V constant, the equation represents the relation between Q and h, and is the equation of a parabola with axis parallel to h (see Plate XIV, curves marked 1). By taking various values for V and drawing the parabolic curve corresponding to each, the relation of the three variables can be readily traced. As may be seen, the vertex of the parabola gradually approaches the axis of h as V decreases. If the assumed form of equation represents the law of variation between the three variables, these parabolas can be adjusted to the experimental results by choosing certain values of the constants K_1, K_2 and K_3.

---

[1] "*Centrifugal Pumps, Turbines and Water Motors*" by Charles H. Innes, 1904, page 243, and "*Zur Theorie der Zentrifugalpumpen*", by Egon R. Grunebaum, page 15.

Similarly, by taking h as constant and assuming various values, the resulting equations show the relations between Q and V for each value of h. These equations represent hyperbolas and as shown on Plate XV, have their transverse axes inclined to the axis of V.

For the determination of the constants K_1, K_2 and K_3, the writers mentioned have attempted to apply the ordinary theory of the centrifugal pump, and the constants are supposed to be capable of evaluation when the form of the impeller and pump casing are known. With more experimental data as to some of the fundamental formulae for loss of head, as for example, loss of head due to sudden change of velocity both in magnitude and direction; and also as to the efficiencies of the outward flow free spiral vortex and of diverging guide passages, it may be possible to evaluate the constants with reasonable degree of accuracy. In the present case the constants have been determined by assuming three points, M, N and O, Plate XIV, on the average curves representing experimental results, speed 1,120 revolutions per minute, and determining the equation of the parabola with axis horizontal passing through these points. To determine the value of K_3 put $Q = 0$, in the assumed equation and obtain:

$$V^2 = K_3 h.$$

substituting numerical values for V and h, and using the foot-second system of units, the value of K_3 equals 76.5. This value of K_3, agrees with the value which may be obtained from the equation

$$V = 1.09 \sqrt{2gh_1}$$

derived from experiment as giving the head of impending delivery. The value 1.09 was found to be constant for all speeds, so the value 76.5 for K_3 will give a parabolic curve, which will pass through the head of impending delivery corresponding to any peripheral velocity V.

The values of K_1 and K_2 were determined by writing two independent equations containing these constants, by substituting in the general equation the numerical value of V corresponding to the speed of 1,120 revolutions per minute, and the Q and h values of the coordinates of the points M and N, then solving for K_1 and K_2. These values of K_1 and K_2, together with that of K_3, when substituted in the general equation, No. 1, gave the relation between Q, V and h.

$$473\ Q^2 - 23.6\ Q\ V - V^2 + 76.5\,h = 0. \qquad (3)$$

For the speed of 1,120 revolutions per minute, $V = 42.8$ feet per second and the equation becomes that of a parabola.

$$473\ Q^2 - 1{,}010\ Q - 1{,}830 + 76.5\ h = 0 \qquad (4)$$

The constants have been so chosen as to make the parabola, for speed of 1,120 revolutions per minute, agree with the experimental results as nearly as possible. (See Plate XIV, curves marked 1.) It will be seen that there is considerable variation between the two curves for low heads, but for heads greater than about one-half the maximum head which the pump will hold up, and which covers the working conditions of the pump, the equation may be taken as expressing the relation between Q and h. In order to compare the actual and theoretical effect of a change in the peripheral velocity, V, on Q and h, values of V, corresponding to the speeds of 1,300 and 1,500 revolutions per minute, have been substituted in equation No. 3 and the resulting parabolas plated on Plate XIV, curves marked 1. At the speed of 1,300 revolutions per minute, an increase of about 15 per cent in speed, there is still quite close agreement between the theoretical and experimental curves, the theoretical curve giving values of discharge, for a given head, about ten per cent greater than the actual. At the speed of 1,500 revolutions, an increase of about 35 per cent in speed, the theoretical values for discharge for a given head, are considerably larger than the experimental, amounting to about 25 per cent.

In order to compare the theoretical and actual relation of Q and V for various heads, values of h equal 20, 30 and 45 feet respectively, have been substituted in equation No. 3, and the resulting hyperbolas platted on Plate XV, curves marked 1.

The hyperbola corresponding to 30 feet head practically agrees with the experimental results, as the constants of the general equation have been assumed of such value as to make this agreement. For a head of 45 feet and speed of 1,500 revolutions per minute, corresponding to an increase in speed of about

35 per cent, the value of the discharge, taken from the curve of the hyperbola, is about 25 per cent too large.

EVALUATION OF COEFFICIENTS FOR GENERAL EQUATION NO. 2

With this form of equation:

$$A\ Q^2 - B\ Q - V^2 + Ch = 0.$$

the parabolas representing the relation between Q and h, for various values of V, have their axes horizontal and located at a constant value of Q. (See Plate XIV, curves marked 2.) The hyperbolas representing the relation between Q and V, for various values of h, also have their transverse axes parallel to the h axis, and located at the same value of Q as the parabolic curves (see Plate XV, curves marked 2). The values of the coefficients A, B and C have been determined in the same manner as the values of K_1, K_2 and K_3. For the speed of 1,120 revolutions per minute, the equation of the parabola showing the relation between Q and h is the same as equation No. 4,

$$473\ Q^2 - 1{,}010\ Q - 1{,}830 + 76.5h = 0.$$

and the general equation No. 2 containing the three variables becomes:

$$473\ Q^2 - 1{,}010\ Q - V^2 + 76.5h = 0 \qquad (5)$$

Comparing the computed results by using equations Nos. 3 and 5, and illustrated by curves marked 1 and 2, Plate XIV, with the experimental results, it may be noted that for a speed of 1,300 revolutions per minute, an increase in speed of about 15 per cent, the computed discharge corresponding to a head of 38 feet, curves marked 1 give results about 10 per cent too large, while curves marked 2 give results about 10 per cent too small. For a speed of 1,500 revolutions per minute, an increase in speed of about 35 per cent, the discharge corresponding to a head 48 feet, curves marked 1 give results about 25 per cent too large while curves marked 2 give results about 20 per cent too small. Curves marked 2 are thus slightly more accurate for large percentage change in speed and apparently agree with the form of the experimental curve somewhat better.

It is worthy of note that an average of the results by the two curves marked 1 and 2 would give very close agreement with the experimental results. Combining equations Nos. 3 and 5, there results as the final equation showing the relation between Q, V and h,

$$473\ Q^2 - \tfrac{1}{2}\ Q\ (23.6\ V + 1{,}010) - V^2 + 76.5\ h = 0 \quad (6)$$

The results by using equation No. 6 are shown, on Plates XIV and XV, as curves marked 3.

The results of the computations show that for the pump experimented with, a pump with free vortex surrounding the impeller, and a spiral discharge chamber, a general equation of either form:

$$K\ Q^2 - K_2\ Q\ V - V^2 + K_3 h = 0,$$

or $$A\ Q^2 - B\ Q - V^2 + Ch = 0,$$

can be adjusted to agree with the experimental results at one speed, the heads pumped against for the given speed exceeding about one-half the maximum head which the pump will hold up, and the resulting equation can be used, with reasonable accuracy, to determine the effect of moderate changes in one or all of the three variables. Also that by averaging the computed results by using the two forms of equations or preferably by combining these two equations into a single equation, the final computed values by using this equation, will be in very close agreement with the experimental results. From the comparisons shown, it would be reasonable to assume that the application of the method described, would give the discharge within about 10 per cent, when the percentage change in speed does not exceed about 50 per cent.

SUMMARY OF CONCLUSIONS FROM PARTS I AND II OF INVESTIGATION OF CENTRIFUGAL PUMPS

Part I—Results of Experiments With Six Inch Vertical Centrifugal Pump

1. The efficiency of centrifugal pumps, and especially of deep well vertical centrifugal pumps, with impellers having radial enclosed vanes, cannot exceed 50 per cent unless some provision is made, by means of a suitable vortex chamber or by guide vanes, for converting the kinetic energy due to the absolute velocity at the outlet of the impeller, into pressure energy.
2. The results of experiments with impellers having radial enclosed vanes, show that varying the number of vanes of the impeller between the Nos. 6 to 24 makes very little difference in either efficiency or capacity.
3. By comparison of the results of experiments, with impellers having radial vanes and the area of cross-section of waterway between vanes, first increasing, and second practically constant, it is shown that there is very little change in either efficiency or capacity. The conclusion is evident, that in the case of the impellers having areas of cross-section of waterway increasing, that the entire cross-section is not utilized for discharge, and that there is a revolving dead water space. The normal component of the absolute velocity of the water at the outlet of the impeller, cannot therefore be computed indiscriminately, by dividing discharge by the sum of the circumferential areas of the outlets of the impeller.
4. For impellers having radial enclosed vanes, the ordinary formulae, $\frac{V^2}{g}$, for determining theoretical head, and $W\,Q\frac{V^2}{g}$, for determining theoretical power input, gave results for the economical working conditions of the pump, too large by about the following percentages:

   for the impellers having 24 vanes, error 10 per cent.
   for the impellers having 12 vanes, error 20 per cent.
   for the impellers having 6 vanes, error 30 per cent.

PART II—RESULTS OF EXPERIMENTS WITH SIX INCH HORIZONTAL CENTRIFUGAL PUMP.

1. Effect of leakage of air. Plate XII: at the economical working condition of the pump, a leakage of air of about .01 cubic feet per second, equal to about one per cent of the volume of discharge, and requiring special means to detect, the effect was a decrease in head of about 10 per cent, a decrease in capacity of about 15 per cent, and decrease in efficiency of about 5 per cent, while for heads somewhat below the economical working condition, with resulting increase in discharge, the effect of leakage of about .04 cubic feet per second, or about 2 per cent of the volume of discharge, was a decrease in head of about 20 per cent, a decrease in discharge of about 20 per cent, and the efficiency remained the same.
2. Comparison of results with spiral case and circular case: Plate XVI: With the speed of the pump at 1,120 revolutions per minute, and for the economical working condition, the maximum efficiencies were 57 and 52 per cent respectively, the spiral case furnishing the most water for a given head by about 20 per cent. For a speed of 1,300 revolutions per minute, the comparison was not quite so favorable to the spiral case, the maximum efficiencies being 54 and 53 per cent respectively, the spiral case still furnishing about 20 per cent more water.
3. Comparison of results of experiments, entrance to pump under pressure and entrance to pump under suction: Plates XIII and XIV. The results of the comparison showed that the curves representing capacity, efficiency, horse power output and horse power input remained unchanged, when the conditions at the entrance to the pump were changed from one of pressure to one of suction.
4. Efficiency of the vortex chamber surrounding the Impeller: The results of the experiments showed that the efficiency of the vortex chamber, increased with the discharge, was about 25 per cent at the economical working condition of the pump, and was a maximum of about 45 per cent for conditions of low head and large discharge.

5. Results of measurements showing rotation of water in the suction pipe near the entrance to the pump; The results with the rotometer showed that a spiral motion was formed in the suction pipe, as the water approached the impeller, and that the absolute velocity of the water at entrance to the impeller, even at the economical working condition of the pump, had a component in the direction of rotation of the impeller.
6. Equation representing approximate law for the discharge of a centrifugal pump, with a free vortex surrounding the impeller and having a spiral discharge chamber; Assuming equations of the form:

   $$K_1Q^2 - K_2QV - V^2 + K_3h = 0$$

   and $$AQ^2 - BQ - V^2 + Ch = 0$$

   where K_1, K_2, K_3 and A, B and C are constants, and Q, V and h represent discharge, peripheral velocity of the impeller and head respectively, the values of the constants may be determined so as to fit the experimental results at one speed. Each of these equations will then represent the relation between Q, V and h, with reasonable accuracy for moderate changes in the variables. By combining the two equations into one, the final equation will represent the relation, for a much larger change in one or all of the variables. The results of the experiments seemed to show, that the discharge may be determined within about 10 per cent when the percentage change in speed does not exceed about 50 per cent.

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SEWAGE PURIFICATION WITH SPECIAL REFERENCE TO WISCONSIN CONDITIONS

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PREFACE

This bulletin has a three-fold object:

First. To supply managers of sewage purification plants with a brief and simple statement of the fundamental principles of sewage purification, and a discussion of the problems arising in the practical operation of plants.

Second. To furnish city officials and others considering the desirability or necessity of installing purification plants in Wisconsin with an insight into the sanitary and legal questions involved.

Third. To present to students of sanitary science the results of a brief study of the operation of various Wisconsin plants.

In the preparation of the matter relating to the operation of plants, periodical and other literature on the subject has been freely drawn upon.

The illustration of the Wauwatosa filters was supplied by John W. Alvord of Chicago, Illinois. The view of the Worcester filter beds was supplied by Harrison P. Eddy of Boston, Mass. The view of the Brocton filters was supplied by X. H. Goodnough of Boston, Mass. The views of the gravity distributor and sprinkler were furnished by Earle B. Phelps of Boston, Mass. The authors desire to thank these gentlemen for their kindness in allowing the reproduction of these views. They also wish to thank the superintendents and others who have furnished samples and data from the various plants studied.

SEWAGE PURIFICATION WITH SPECIAL REFERENCE TO WISCONSIN CONDITIONS

THE SEWAGE PROBLEM

The problem of disposing of domestic organic waste material is one of the most important ones affecting the public health of communities. It has, from remote times, been studied by sanitarians, and codes of rules have been formulated for its solution. One of the most popular and effective methods of disposal employed has been the removal of the wastes to a place sufficiently far from the community to preclude any possibility of nuisance arising from them, but the comparatively recent practice of diluting the wastes with large quantities of water and conveying them, in solution and in suspension in the liquid, through sewers to a convenient point of disposal has introduced new factors into the problem. The tremendous increase in the volume of matter to be dealt with, occasioned by the dilution with water, has made it impossible to confine the wastes to a limited locality, but instead, the sewage is necessarily turned into some drainage channel, to the jeopardy of the lives and health of other communities.

The discharge of a relatively small amount of sewage into a stream brings about no serious conditions; but, as the amount of sewage increases, due to the building of new sewer systems and an increase of population, the water of the stream becomes discolored; a greasy scum appears on the surface, foul mud is deposited on the bottom, and the stream becomes offensive and dangerous.

As the custom of discharging raw sewage into water courses becomes more prevalent, the difficulty of securing pure water for stock and for domestic use increases. In fact, the protection of streams and lakes from pollution by sewage has become one of the great problems of the present day, for the use of impure water for domestic purposes is responsible for a large percentage of all sickness and deaths. It is a very important cause of diarrhoea, typhoid fever, cholera, and probably a number of other diseases.

Typhoid fever, for example, is caused by the infection of the human body by microscopical organisms known as bacteria or germs. This disease may localize in various parts of the body, but most commonly the small intestine is the principal seat of its development. It is apparent that large numbers of the bacteria of this disease naturally find their way into sewage through the dejecta from the body. Unfortunately, they do not die immediately on leaving the body, but maintain their power for harm for considerable lengths of time. It has been determined that they will retain their vitality in water for eight or nine days. We have it from the highest authorities in preventive medicine, that of all diseases, typhoid fever and smallpox come the nearest to being preventable. Typhoid fever could be practically abolished by preventing the pollution of our milk and water supplies. Other diseases may be caused in the same way by the growth of some bacteria in the body, while still others may be caused simply by the irritation caused by poisons in the water.

Sewage works in the United States, are not usually expected to turn out an effluent satisfactory for use as a water supply; but the passage of the sewage through the works should result in a great reduction in the number of bacteria present and in the prevention of unsanitary conditions in the stream receiving it. To entirely remove the bacteria would require some method of sterilization, or very expensive filtration works, and the adoption of either of these methods has not been considered practicable at the present time. But in those places where it is necessary to use a stream receiving sewage, as the source of domestic water supply it is found that there is an economic advantage to be gained as well as a greater factor of safety, as far as bacterial efficiency of the water filters is concerned, by the partial purification of the sewage before turning it into the stream.

In some places the sewage-polluted water is not used for drinking or bathing or for watering stock, and the danger of infection is therefore slight, but even in such cases serious pollution of the water cannot be tolerated near dwellings or places of employment on account of the offensive odors produced, which cause depreciation in the value of adjacent property and inconvenience to persons in the vicinity.

THE LAW REGARDING SEWAGE DISPOSAL

Every person has the legal right to the fullest enjoyment of his life and health, and anything wrongfully done or permitted which injures or annoys another in the enjoyment of his legal rights is said to be an actionable nuisance. The discharge of sewage by a person or a community into any body of water, by reason of causing foul odors or other unsanitary conditions, may be considered a nusance and render the person or corporation causing the nuisance liable to legal action. The following court decisions are cited as illustrations:

Putting deleterious and offensive substances in a stream is a nuisance and is ground of special damages to a land owner below. (*Greene vs. Nunnemacher,* 36 *Wis.* 50.)

The deposit of refuse from a creamery into the bed of a stream flowing through plaintiff's land and near his buildings, polluting the water and giving off noxious gases affecting the use and enjoyment of plaintiff's property, is a nuisance.

A creamery company will be enjoined from causing offensive waste matter to flow upon another's pasture to its injury. (*Price vs. Oakfield Highland C. Co.,* 87 *Wis.* 536.)

Where a manufacturing establishment in its operations discharges large quantities of deleterious substances, thereby polluting a stream and destroying the fish, and such injurious substances intermingle with the water and render it less available for purposes of agriculture and stock raising, such an act constitutes a public nuisance. (72 *N. E. Rep.*, 879.)

From the conflict of the right of the city to dispose of its sewage and to make reasonable use of public water courses for that purpose and that of the riparian owner to have the water come to him in substantially its natural state arises the well established rule that a city may empty its sewers into such bodies of water, but cannot do so in such a way as to create a nuisance, without incurring the liability to parties specially injured thereby, and being liable as well to indictment on behalf of the public, if the nuisance is a public one. (*Central Law Journal,* 48: 92.)

In considering the cases against the village of Saratoga, N. Y., the court followed closely the axiom that a riparian owner has a right to the flow of the stream as "it is wont by nature," and a contributor of pollution is liable for damages regardless of other pollution or the diluting effects of the stream. The court gave judgment in favor of the plaintiffs, awarding a sum for past damages and so much a year from the time of the trial, as long as the nuisance lasted. The total damages paid by the city of Saratoga Springs exceeded $20,000. (F. A. Barbour, *Jour. Assoc. Eng. Socs.*, **34**: 33; Feb., 1905.)

The mere fact that a city's sewers are of permanent construction does not render permanent also the nuisance occasioned by them, such as poisoning the water of a stream and so injuring the stock in pasture, for in such case, the city has a right at any time to abate the nuisance by proper means of filtration or otherwise using such sanitary measures as to render the sewage innocuous.

In the case of *Smith vs. Milwaukee*, 18 *Wis.*, p. 63, the court states that a municipal corporation is liable for a nuisance caused by neglect to provide sewage disposal.

In the state of Wisconsin, the circuit courts have jurisdiction of actions to recover damages for, and to abate private nuisances or a public nuisance from which any person suffers a private or special injury, peculiar to himself, so far as necessary to protect the rights of such person, and to grant injunctions to prevent the same.

In addition to the general law relating to nuisances, special legislation has been enacted in the interest of the public health. Thus we find that in Wisconsin it is incumbent upon the State Board of Health to investigate the sanitary conditions of sewage disposal and water supplies, and to advise local authorities relative to the sanitary construction and management of the same. The state board has power to make rules and regulations pertaining to the carrying into effect of any law passed by the legislature, and the laws of 1905 further provide that any person who shall neglect or refuse to obey such rules and regulations, or who shall willfully obstruct or hinder the execution thereof, shall be punished for each offense by a fine of not less than twenty-five dollars nor more than five hundred dollars, or by imprisonment in the county jail for not more than six months, or by both fine and imprisonment.

All plans for sewerage systems and for sewage disposal works must be submitted to the State Board of Health for approval. The degree of purification which the board will insist upon in any particular case depends upon the local conditions at that place.

DEGREE OF SEWAGE PURIFICATION REQUIRED

Mr. Elliott A. Kimberly suggests[1] the following general rules to govern the needed degree of purification of domestic sewage.

"1. Where the sewage effluent is to be discharged into running streams subject to floods and with a water containing considerable turbidity, at all seasons of the year, the degree of purity required need not be more than that of an effluent which undiluted will no longer putrefy under summer conditions.

"2. In streams, the water of which are clear except at times of flood, the purification of the sewage should be such as to remove from it the largest practicable quantity of suspended matter, so that the visible purity of the stream will not be affected, the non-putrefaction of the effluent being taken as coincident with a degree of purification which will afford an absence of all but small amounts of turbidity.

"3. In drinking water streams, and in certain cases of sea discharge where shell fish layings must be protected from contamination, the purification of the sewage must needs be carried out to its fullest extent, and besides the production of a chemically stable effluent, the problem practically reduces itself to the destruction of all the disease producing bacteria present in the raw sewage, by subjecting the well purified effluent to some form of sterilization process."

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[1] The Use and the Abuse of Sewage Purification Plants.

SEWAGE PURIFICATION METHODS

Mention has been made above of the fact that sewage discharged into a stream will not ordinarily cause a nuisance, provided the quantity of sewage is small relatively to the volume of flow in the stream. This is accounted for by what is called *self purification.* Such purification is brought about largely through the oxidation of the impurities by the air in solution in the water and through the sedimentation or settling of the impurities by their own weight or the weight of particles of mud to which they have become attached, to the bottom of the stream where they are later acted on by living organisms in a way to be described below. Sunlight, too, has great effect in killing disease germs in the water and in causing chemical action to take place in the other impurities. But all these processes require much time. Currents in the water prevent the rapid settlement of impurities; the sun is unable to penetrate far into muddy or impure water, and the air does not readily become mixed with it; so impure water sometimes remains impure for long periods of time. The Rivers Pollution Commissioners of England estimated that sewage mixed with twenty times its volume of pure water would be only about two-thirds purified in a flow of 168 miles, at the rate of one mile an hour. On the other hand, it has been claimed that a satisfactory degree of purification is secured in the case of the sewage of Chicago in a relatively short length of flow after diluting it with lake water in the sanitary canal. In the cases of bodies of water like lakes and large reservoirs, where the currents are very sluggish, sedimentation is more effective.

Chemical Methods

Some of the earliest methods used for artificially treating sewage in large quantities were chemical in character. In these methods proper amounts of certain chemicals, such as lime, alum and iron, were added to the sewage; the chief result being that the impurities in suspension were more or less changed in nature and were caused to settle to the bottom of a settling tank.

On account of the large amount of sludge produced in the tank and the cost of the chemicals used, this method has not become popular for treating domestic sewage, but for some classes of trade wastes it is the only method practicable.

BIOLOGICAL METHODS

The principal methods of artificial treatment of sewage in use at the present time are biological; that is, they depend on the action of living organisms, principally certain bacteria. As before stated, some diseases are caused by bacteria or germs, but all bacteria do not produce diseases; some are very useful. The various kinds of cheese, for example, are produced by cultivating the growth in milk of different kinds of bacteria, which by their action on the milk change its nature. Just so, in sewage treatment, the problem is to so arrange the conditions as to promote the development of the proper kinds of bacteria. For instance, some bacteria thrive only when deprived of air, as in a closed vault; these are called anaerobic. Others develop only where they can have air, and these are called aerobic. All sewage contains immense numbers of bacteria, and if they are given proper opportunity to work they will reduce the impurities, which are largely organic, that is, composed of animal or vegetable matter, to harmless mineral matter.

The first action on the organic matter in sewage must be by the aerobic bacteria, because of the air and free oxygen dissolved in the sewage. By their action these bacteria soon use up the dissolved oxygen in the sewage and their action is therefore slight, at this stage of the purification, but is replaced by the action of the anaerobic bacteria for which the conditions are then suitable. The anaerobic bacteria have the power of liquifying the solid organic matter, just as a rotten apple is liquified and runs away, and hence are sometimes called liquifying bacteria. This action is very important, for if it can be made thorough, it will do away with the problem of handling the solid matter in the sewage. If the purification is to be carried farther, the sewage must be aerated in order to supply the oxygen required by the aerobic bacteria, which will again increase in numbers when the conditions are suitable for their development. These bacteria act on the matters dissolved in the water of the sewage, combining them with oxygen and producing stable mineral substances.

In addition to the bacteria, there is action by a class of substances called *enzymes*, which, though not living, are products of animal and vegetable life. Pepsin is a familiar example of an enzyme. Enzymes are formed by moulds, larger fungi, and by plants and animals as well as by bacteria.

Under some conditions, these products of the bacterial life promote the purification of the sewage, while at other times they hinder it.

SEWAGE PURIFICATION SYSTEMS

Only the systems based on the biological method of treatment will be considered here.

In designing sewage disposal plants based on this method, the aim is to make the sewage pass through various structures so arranged as to afford the proper conditions for the growth and operation of the different classes of bacteria described above, and in the order most advantageous. Naturally in the development of this new art of sewage disposal, considerable diversity of opinion has at times arisen as to the best devices and arrangements to promote the desired aim, and we accordingly find great variety in the details of existing plants, according as natural conditions, the character of the sewage, or the ideas or knowledge of the designer varied. Part of the diversity in design is due to the fact that a large number of patents have been secured covering apparatus and methods of disposal, necessitating either the payment of royalties or ingenuity in avoiding infringement of the patents. It seems the latter course has generally been preferred.

Filtration

Sewage Farms. In some cases the crude sewage is applied to the surface of agricultural land, on which crops are still raised. This method of disposal is known as surface irrigation. The sewage in flowing over the surface is acted upon principally by aerobic bacteria which exist in large numbers in the upper layers of the soil. This system requires very large areas of land. Where the ground is porous, underdrains may be laid, and then larger quantities of sewage may be applied. Under the latter conditions, the sewage, instead of flowing over the surface, seeps through from the surface to the underdrains. The sewage should be applied intermittently to allow air to enter the soil between the doses of sewage. Where land is used in either of these ways, it is known as a *sewage farm.* Sewage farms are rare in the United States, but this method of disposal will doubtless be popular in the arid regions of the west on account of the value of the water in the sewage. Examples of sewage farms in the east may be found at Vassar College near Poughkeepsie, N. Y., and at Meriden, Conn. It is more customary, in the United States, to construct artificial filters, in which the size of grain and nature of filtering material is under control. The area of artificial filter required is usually much less than in the case of natural soil, owing to the more uniform grading of the filtering material in the former. An artificial filter which treats crude sewage is in operation at the National Soldiers' Home at Milwaukee.

Artificial filters differ greatly in the nature and size of grain of the filtering material of which they are composed, and also in the principle according to which they are operated. Thus we have *contact beds* of either fine or coarse material, *percolating filters* and *trickling filters.*

Contact Beds. The filtering material of contact beds is contained in a water-tight reservoir, in which the sewage is retained for some hours by closing the outlet valves. In this type of filter the solid matter is not strained out of the sewage, for the passages between the grains of the filter are usually much larger than the particles of solid matter in the sewage, and furthermore the sewage is often let into the contact bed at the bottom, sometimes through the same pipes through which it is again drained out, thus precluding any true straining action. A large part of the solids of the sewage are nevertheless filtered out of the sewage by the contact bed. The action is brought about by the solids of the sewage settling onto or adhering to the grains of filtering material with which they come in contact. As the reservoir is emptied of sewage, the solid matter is retained in the filter, but air is drawn down into the filtering material, by the removal of the liquid, and this thorough aeration enables the bacteria, which swarm in the filter, to consume a large part of the retained solid matter. Also when the next dose of sewage comes into the contact bed, the bacteria which have so recently been thoroughly aerated are able to oxidize large amounts of the impure matters which are dissolved in the sewage.

A contact bed, as suggested by John. W. Alvord, resembles nothing else so much as a huge lung. The emptying and filling of the liquid in the contact bed corresponds to the inhaling and exhaling of a breath, and as the indrawn air in the lung oxidizes the impurities of the blood through the thin walls of its tissue, so does the entrained air and bacteria in the contact bed do its work upon the dissolved impurities in the sewage.

Percolating Filters. Percolating filters are made of a fine grain material, such as sand or screened cinders, and the sewage is applied to the top, as in a sewage farm, and allowed to seep through to the underdrains below. In this type of filter, a straining action takes place on account of the small size of the passages between the grains of filtering material, and large amounts of solids are retained on or very near the surface; the passages being too small to allow the solids to penetrate far into the body of the filter. While the sewage is percolating through, the passages in the filtering material are entirely filled with sewage and the air is excluded. It is therefore necessary to operate the filters intermittently, as in the case of contact beds, so as to give opportunity for air to be drawn into the filter to supply the oxygen required by the aerobic bacteria which act on the dissolved impurities in the sewage as it seeps through.

Trickling Filters. Trickling filters are composed of coarse grain material and the sewage is applied at a slow rate, usually by sprinkling it onto the surface of the filter, so that at no time do the pores of the filter become filled with sewage, but it simply trickles over the surface of the grains in a thin film. Air is at all times drawn into the filter by the sewage trickling through it, and on account of this continuous supply of oxygen to the bacteria, the filter may be operated continuously.

In all of the above classes of filters and sewage farms, the central idea is to afford means of supplying to the aerobic bacteria the air that they require in order to consume or oxidize the organic matter in the sewage. Each type has its advantages and disadvantages, some of which will be mentioned later in connection with the operation of plants.

PRELIMINARY TREATMENT

As before mentioned, the aerobic bacteria act principally upon organic matters which are in solution. Such solid matter as is in suspension in the sewage is not readily attacked by them, and as the conditions are not suitable for the development of the anaerobic, or liquifying, bacteria, the solid matter which reaches the filter is likely to be retained and accumulate in or on the filter. It is true that there is usually some action by the anaerobic bacteria in the interior of masses of solid matter where they are protected from the air, but such action is not sufficiently rapid to keep pace with the accumulation of solid matter, and hence filters have a decided tendency to clog, especially when crude sewage is applied to them. It is customary, therefore, to give the sewage some preparatory treatment to remove, as far as possible, those matters which prove detrimental when applied to the filters.

Screen Chambers. Coarse floating matter may be retained by a screen chamber such as the one shown in Figure 1, which consists of two channels, either one or both of which may be used, the sewage being diverted from one to the other by means of stop planks. In each channel are two screens constructed of steel bars; the first screen has openings of ⅝-inch and the second openings of ¼-inch. The screens are inclined down stream at an angle of 60° with the horizontal. The screenings are to be conveyed in a wheelbarrow to an area reserved for their disposal.

Grit Chambers. Grit and other heavy suspended matter may be caught and retained in a grip trap, which usually consists simply of an enlargement in the cross-section of the sewage carrier so arranged as to produce a sufficiently slow velocity of flow as to allow the sedimentation of the grit. A sand trap arranged to be built in the line of an open canal is illustrated in Figure 2. The flow would be from the left, in the longitudinal section, to the right, out over the horizontal flashboards, which can be arranged as a wier to measure the flow. The grit will be deposited in the depression to the left of the flashboards, and can be periodically discharged through the 8-inch pipe at the bottom by raising the gate.

Sedimentation Tanks. In a great many cases a more thorough sedimentation of the grit and also of the organic suspended matter is caused to take place by providing a large sedimentation chamber or tank. This class of tank has been variously named

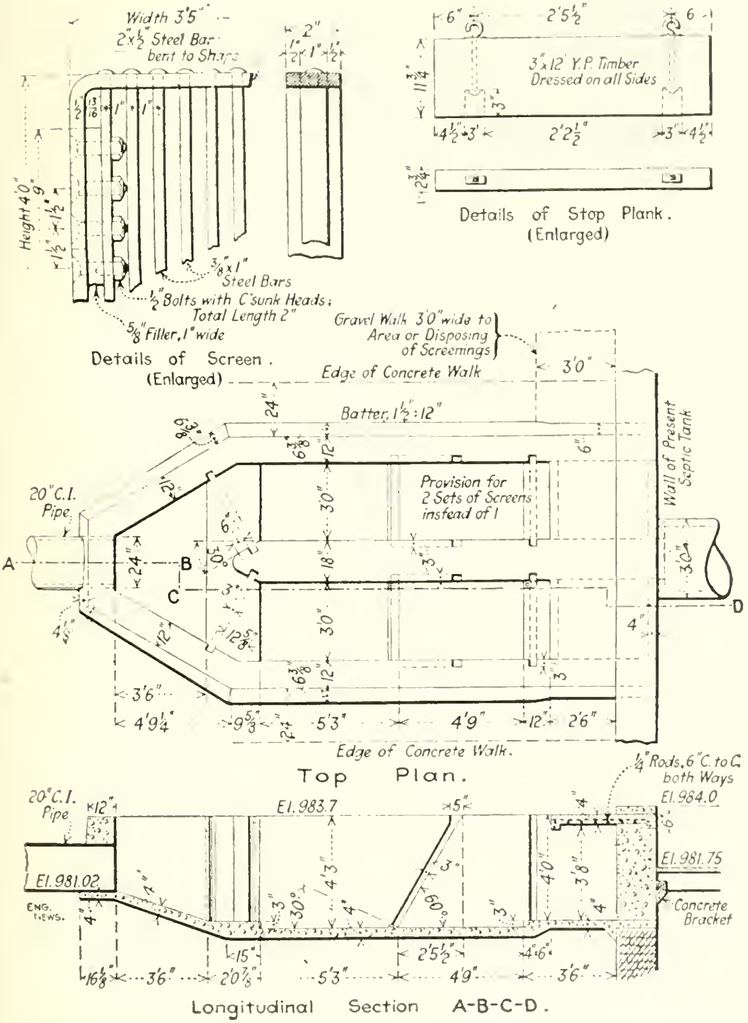

Width 3'5"
2"x½" Steel Bar bent to Shape
Height 4'0"
⅜"x1" Steel Bars
½" Bolts with C'sunk Heads; Total Length 2"
⅝" Filler, 1" wide
Details of Screen. (Enlarged)
3"x12" Y.P. Timber Dressed on all Sides
Details of Stop Plank. (Enlarged)
Gravel Walk 3'0" wide to Area or Disposing of Screenings
Edge of Concrete Walk
Batter, 1½":12"
Provision for 2 Sets of Screens instead of 1
Wall of Present Septic Tank
20" C.I. Pipe
A
B
C
D
Edge of Concrete Walk.
Top Plan.
¼" Rods, 6" C. to C. both Ways
El. 984.0
El. 983.7
El. 981.75
El. 981.02
Concrete Bracket
ENG. NEWS.
Longitudinal Section A-B-C-D.

Figure 1.—Details of Screen Chamber, Sewage Purification Works, Washington, Pa.

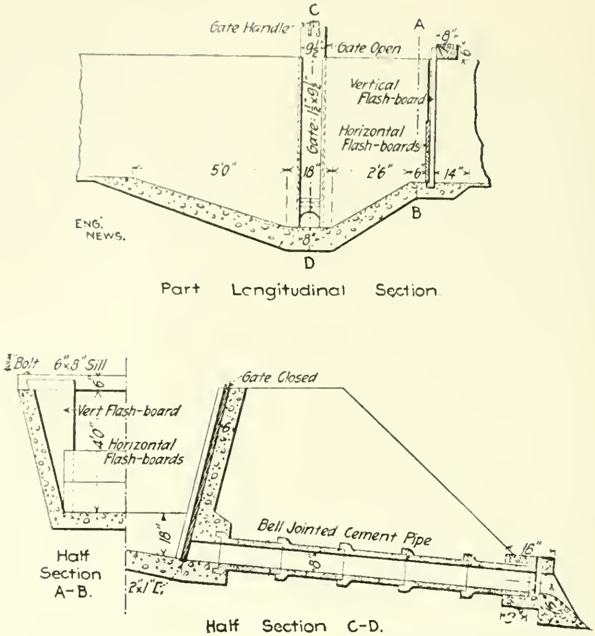


FIGURE 2.—GRIT TRAP IN OPEN CHANNEL, DULZURA CONDUIT.

by different designers as *settling basins* and *sedimentation tanks,* or as *bacterial tanks, reduction tanks* or *septic tanks,* etc., according as emphasis is laid on one or another of the actions that go on in them. If the accumulated solids, technically known as *sludge,* are removed often, the tank should be known as a *settling tank* or *sedimentation basin.*

Septic Tanks. If the sludge is held long enough, a vigorous growth of bacteria will develop in the organic solids present, and these bacteria will break down the solids into gases and matters which are principally soluble. Such a reduction of the impurities is known as septic action. If such action is encouraged to become prominent, the tank should be termed a septic tank. The term *septic* as applied to tanks for the treatment of sewage was originally given by Donald Cameron to a tank, in his patented process, in which the sewage was supposed to be subjected to the action of anaerobic bacteria alone, but the term is commonly used now for tanks in which it is intended that septic action should occur, regardless as to whether that action is caused by aerobic or anaerobic bacteria.

In large purification plants where surface drainage finds access to the sewers, it is best to pass the sewage through a grit trap before its entry to the septic tank, but in small places where the separate system of sewerage is used, the grit trap and screen chamber are best omitted as they are likely to become foul from floating material unless given considerable attention.

Anaerobic Filters. A modification of the septic tank is the anaerobic filter which is operated continuously and is at all times full of sewage. The air is, therefore, excluded and action is caused principally by the anaerobic bacteria.

The dosing of contact and intermittent filter beds requires regularity, in order to provide time for draining and aeration. The emptying and filling by hand operation of gates, though successful in a few instances, has generally proved unsatisfactory, especially in the smaller plants, on account of the close attention required. A number of automatic devices have, therefore, been devised for the purpose of controlling the discharge on to the beds.

COMPLETE SEWAGE TREATMENT

The complete treatment of sewage would involve its passage through, first, a grit trap and screening chamber; second, a septic tank; third, a coarse filter; fourth, a fine filter. In none of the disposal plants built in Wisconsin does the design provide for such a complete treatment, but various combinations of the devices mentioned have been used according to the requirements as to degree of purification or the designer's estimate of the character of sewage to be treated at the different localities.

In many cases, in addition to the domestic sewage, trade wastes, such as those from creameries, slaughter houses, breweries, dye works, paper mills, tanneries, etc., enter the sewers. These wastes are generally more difficult to treat than the domestic sewage which is already partially digested and full of bacteria when it reaches the sewers. Even the domestic sewage varies greatly in strength and composition in different communities. The proper selection of a method of treatment and apparatus suitable for any particular sewage is a problem requiring thorough investigation and the application of expert knowledge.

SEWAGE PURIFICATION PLANTS OF WISCONSIN

A number of modifications in design are illustrated in the Wisconsin plants described below.

At the National Soldiers' Home, Milwaukee, was constructed in 1892 or 1893 a plant consisting of filter beds only. These beds are 6 ft. deep and are composed of fine filtering material and are operated intermittently, the crude sewage being applied directly to the surface of the beds without previous treatment, except a rough screening.

The plant at Waukesha, located about a mile from the city, consists simply of a septic tank from which the sewage flows directly into the head waters of the Fox River of Illinois, which here is a very small stream during dry seasons. This septic tank, which was probably the first in the state, was built in 1901 by the city in compliance with a court order growing out of a suit brought by lower riparian owners.

At the Wisconsin State Hospital for the Insane, at Mendota, a plant was built in 1904, consisting of two septic tanks and four filter beds. The plant was built in duplicate to facilitate cleaning and repairing. The sewage from the institution, of about 600 persons, passes directly into the tank, which is located less than 1,000 feet from the main building. From the tanks the sewage flows in a thin sheet over the end wall into the dosing chambers, and when the latter chambers are full they automatically discharge, through siphons, onto the filter beds, which are here composed of coarse cinders. After passing through the filters, the sewage is collected by drains in the bottom of the filters and is led to an outfall which conveys it to Lake Mendota.

At Lancaster (population 2,500), Wauwatosa (population 3,000), the Milwaukee County Institutions (population 2,500), and some other places, the plants are in general similar to the one at Mendota Hospital except in the particular that the filter beds have their upper layers composed of clean sand.

The Lancaster plant is illustrated in Figure 3. The sewage at this plant first passes through a grit trap to remove the sediment from road washings, some of which find access to the

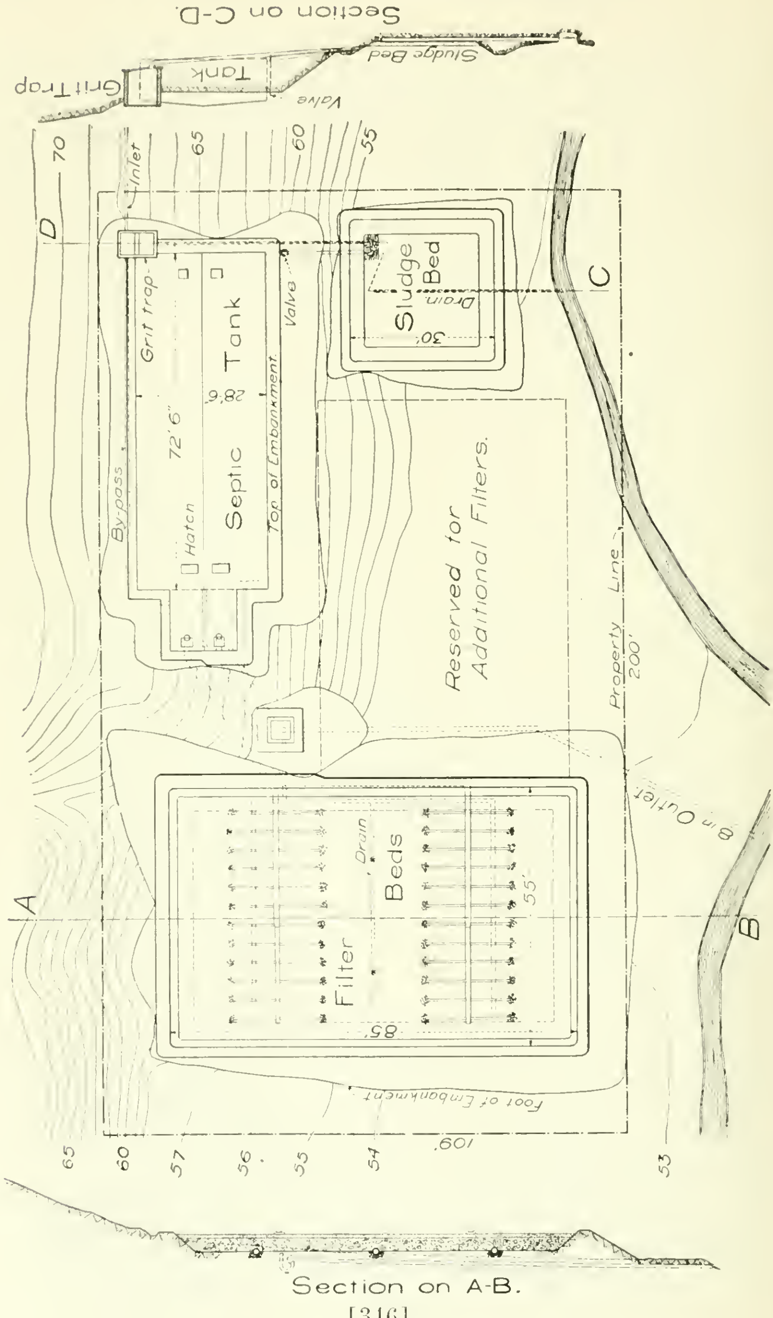


Figure 3.—Plan of Municipal Sewage Disposal Plant at Lancaster, Wis.

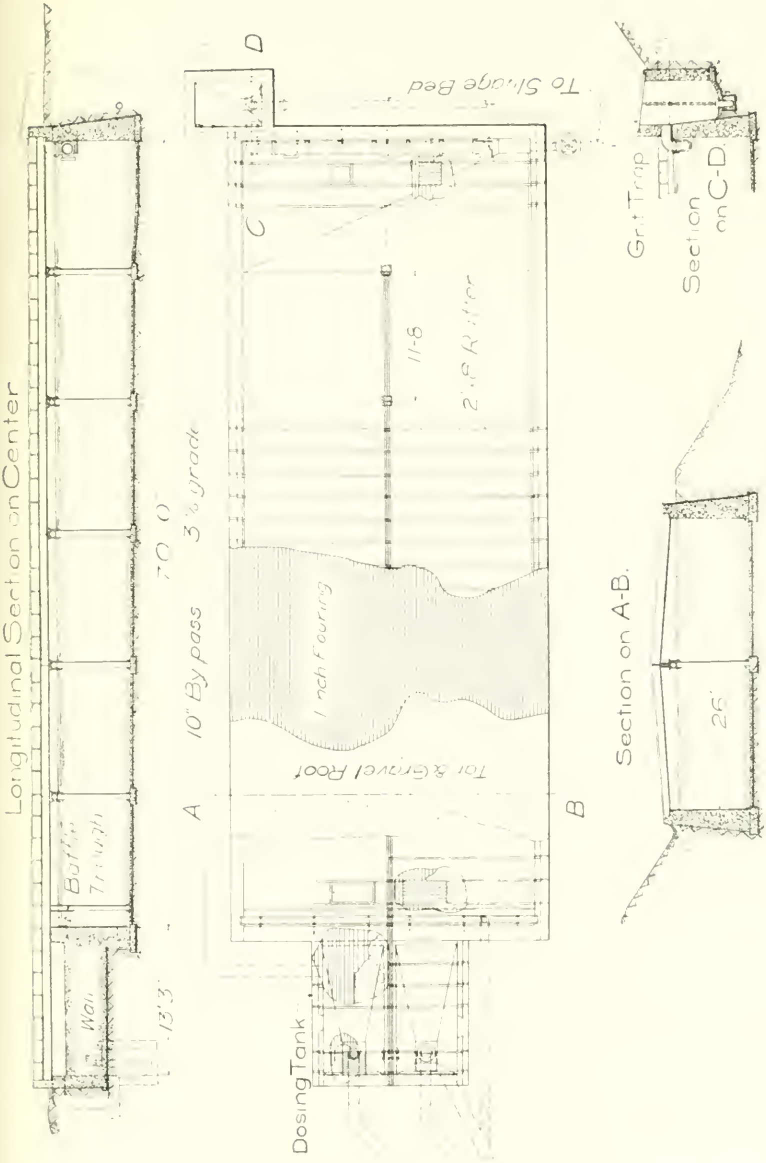


FIGURE 4. SEPTIC TANK AT LANCASTER, WIS.

sewers. It then passes through a septic tank to two dosing chambers from which it is discharged onto the sand filters through vitrified pipe. The filters are composed of 2½ feet of broken stone covered with one foot of sand. Under-drains carry the purified effluent from the filters to the creek. A gate chamber is provided between the septic tank and the filters, by means of which the tank effluent may be diverted to the creek without being filtered. The sludge bed is conveniently located for receiving the sludge from the septic tank and the grit chamber. The septic tank is shown in detail in Figure 4.

The plant at Fond du Lac (population 15,000), was built in 1902, because of a nuisance created in discharging the sewage into the sluggish Fond du Lac river, a tributary of Lake Winnebago. It consists of septic tanks and contact beds. It was intended that the effluent from the tanks should flow into a concrete canal approximately 300 feet long and about 5 feet wide. This canal was to serve as a reservoir and dosing tank for the beds which consist of a depth of 3½ feet of coarse cinders surrounded by earthen embankments. It was intended that the main carrier should fill to a definite height and then, by opening a sluice valve, allow the dose to pass on any desired bed, there to remain in contact with the filtering material until the underdrain for that bed is opened. The presence of a man to operate the sluice gates is needed when the beds are operated as planned. The filters have been operated only a few months since they were constructed, on account of troubles due principally to faulty construction.

The sewage purification works at the plant of the Allis-Chalmers Company, at Milwaukee, consist of four concrete septic tanks, four anaerobic filters and trickling filters. Below the tanks the sewage is aerated by fall over wiers and some steps and enters the anaerobic filter from the bottom. From here the sewage passes to the siphon chambers which discharge it onto the trickling filter below.

The Madison (population 28,000) disposal plant was built as the result of law suits growing out of the nuisances caused by discharging the city sewage into Lake Monona. The plant as first built and operated in 1899 and 1900 used the principles

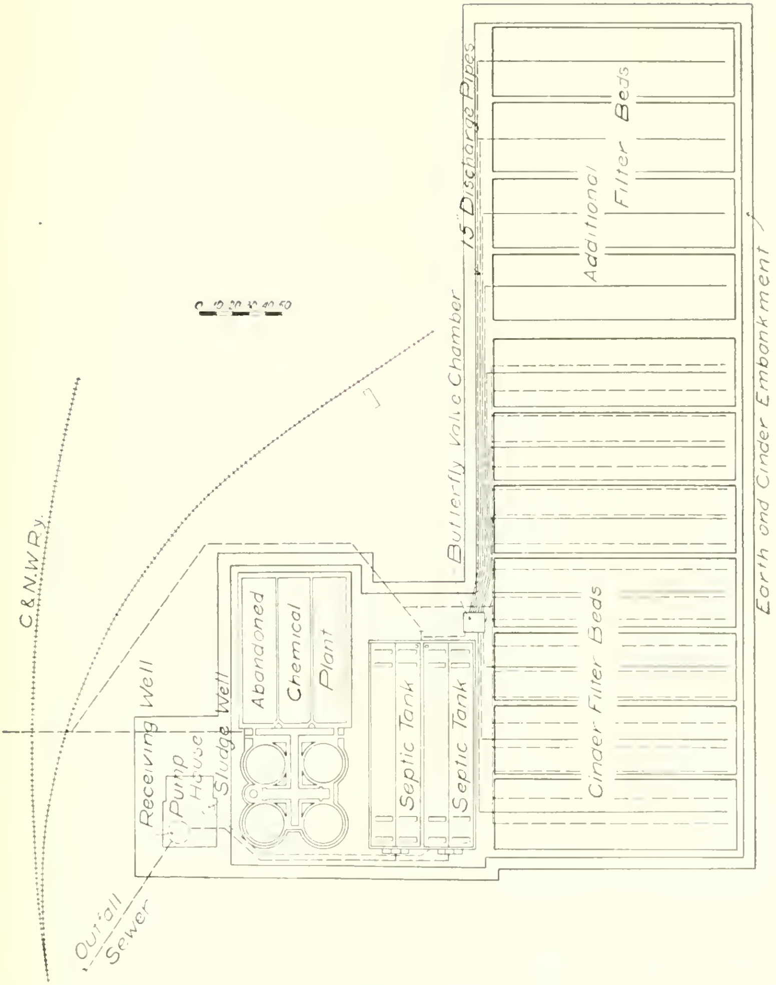


FIGURE 5.—PLAN OF MUNICIPAL SEWAGE DISPOSAL PLANT AT MADISON, WIS

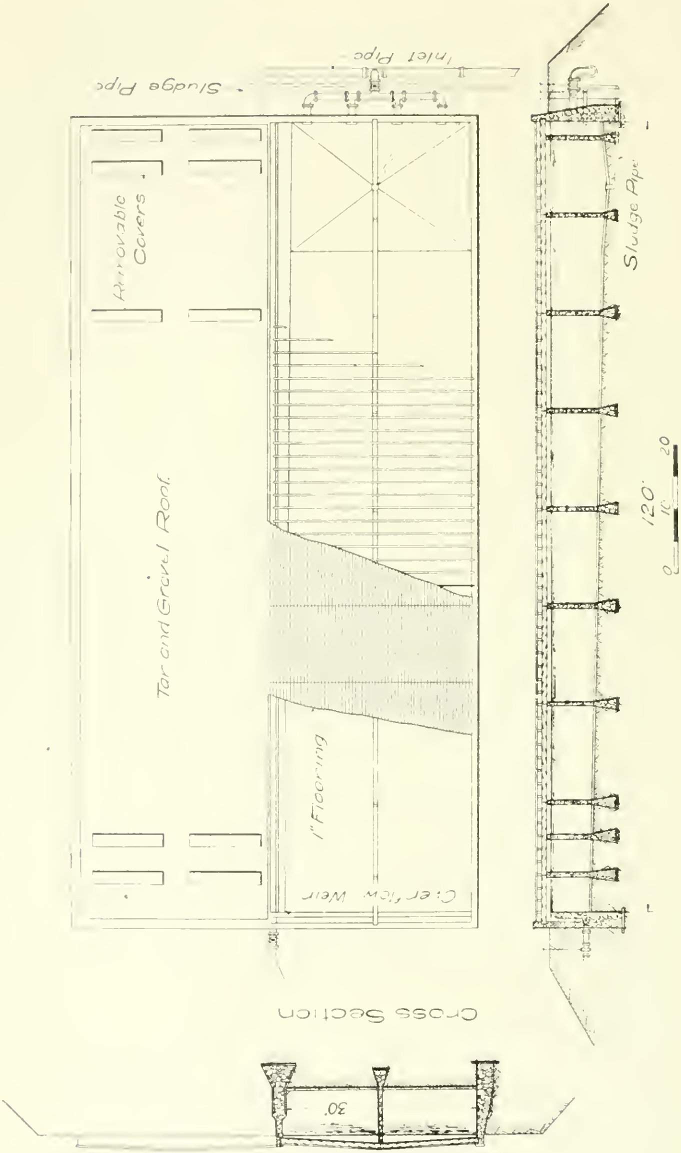


FIGURE 6.—SEPTIC TANK AT MADISON, WIS.

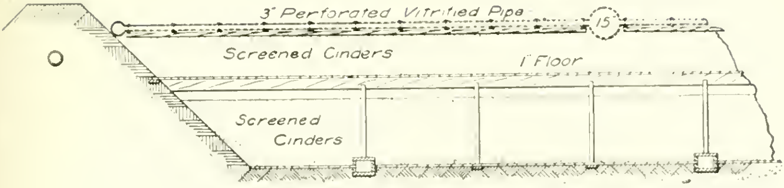


FIGURE 7.—SECTION THROUGH OLD FILTER BEDS AT MADISON.

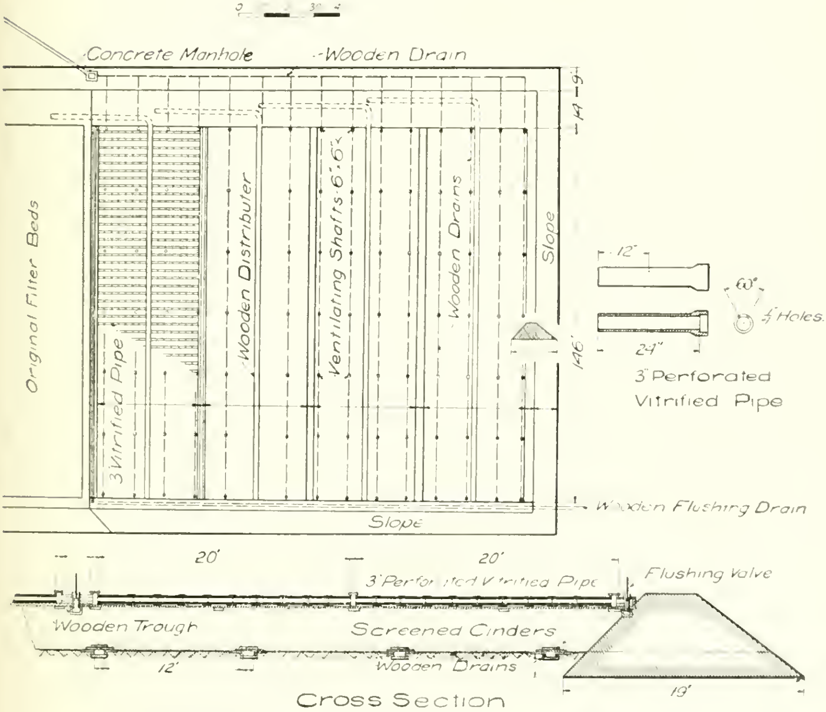


FIGURE 8.—NEW FILTER BEDS AT MADISON.

of chemical precipitation, but, this method proving to be very expensive, it was decided to abandon the plant and substitute for it one based upon the biological method of treatment. The plant as now operated consists of two septic tanks and eleven filter beds, and is shown in plan in Fig. 5, the tank being shown in detail in Fig. 6. The filters are all composed of screened cinders, but the seven beds constructed in 1901 and 1902 differ from the four built in 1905, as may be seen by referring to Figures 7 and 8. The older beds consist of a floor of one-inch rough hemlock boards, with wooden under drains every 16 feet; a lower bed of fine cinders 2 feet deep; a second or upper floor of one-inch boards 4 inches wide, with ¼ inch openings between them; an upper bed of coarse cinders 2 feet deep, and a distributing system of 3-inch perforated vitrified pipe. The upper 6 inches of the upper beds and the entire lower beds are composed of screened, head-end locomotive cinders which had passed through a ½ inch mesh revolving screen, but were held on a ⅜ inch mesh. The lower two feet of the upper beds were composed of cinders passed through a screen with 1-inch mesh and were held on a ½-inch mesh. To distribute the sewage on to the beds, a line of double wyes, decreasing in diameter from 15 inches to 8 inches, was laid down the middle of each bed. Three-inch, perforated, vitrified pipe laid on 2-inch planks branch from the wyes and end in a line of tees, every seventh one of which is a cross, connected to a flushing valve. When a dose of septic tank effluent is discharged on to a bed through this system of piping, a fountain of sewage spurts from each hole in all the 3-inch pipes. The distribution of the sewage over the beds is perfect, but trouble has been experienced with freezing of the 3-inch tiles, when the beds are operated in winter.

The four newer beds added to the plant in 1905 differ in several respects from the older ones. The new ones are solid from top to bottom and are only 2½ to 3½ feet deep; the variation in depth being due to the slope of the bottom. The upper twelve inches are clean, head-end locomotive cinders; the remaining cinders being a mixture varying from one-half inch to one and one-half inches, free from dust and dirt. The main distributor and the flushing drains instead of vitrified pipe are made of 2-inch plank. This has been found to be an improvement, there being less breakage of tiles at the connection with the wooden drains and distributors than when vitrified tile was used.

In instances where extensions of the sewer systems have been built and connected with the plant, increasing the amount of sewage it has to treat, without corresponding increases being made in its capacity, the effectiveness of the plant is greatly diminished. This is shown in the case of the Madison plant. Ever since its construction, this plant has received unusually good care and has been maintained at all times in excellent condition, but soon after its completion, large additions were made to the sewerage system of the city, so that at the present time three or four times as much sewage is passing through the plant as it was originally designed for. The result is that, on an average, only about 40 per cent. of the suspended solid matter is removed in the septic tank, while in 1901 analyses showed a removal of about 60 per cent. of the solid matter. The city has recently purchased property and is contemplating the construction of a larger plant.

The majority of the Wisconsin plants are of sufficient size, but only a few of them are doing satisfactory work, owing principally to lack of care.

THE OPERATION OF SEPTIC TANKS

It has been deemed desirable in most of the Wisconsin plants to remove, as far as practicable, all the solid matters in the sewage before treating it by filtration or by dilution in natural water courses. Usually an attempt has been made to effect this removal by means of a septic tank, so arranged as to retain the floating matter and to effect the simple sedimentation of the heavier matters to the bottom. This removal of the solid matters from the sewage is the principal object of the tank. A secondary object is to reduce these solids, just so far as possible, to liquid or gaseous form, so as to reduce to a minimum the expense of handling the sludge. There is usually also considerable action in the septic tank on certain of the impurities of solution, but the main aim should be to operate the tank so as to most effectively dispose of the solids; the action on the liquids being of secondary importance.

The problem of retaining the solid matters in the tank is usually fairly satisfactorily solved by placing *scum boards* near the outlet end to retain floating matter, and proportioning the tank so as to give very gradual and uniform motion of the sewage from the inlet to the outlet. Some septic tanks are not designed so as to fulfill this condition. John W. Alvord reports that experiments with coloring matter showed that with wide or deep tanks the average velocity was greatly exceeded by the velocity through a certain defined zone or path.

Attempts have been made to produce a uniform velocity through the tank by admitting the sewage in a large number of small streams quite evenly distributed over one side or end of the tank, also by means of baffle walls, but experiments showed that no arrangement of baffle boards was wholly able to overcome this difficulty. The best results were found to be obtained when the entering flow was subdivided into several separate streams in parallel compartments. A so-called elastic tank was therefore designed having several long compartments which could be operated singly, in duplicate or in triplicate, or continuously as one long tank.

The secondary object of the septic tank, namely, liquifying or gasifying the solids, is not so well understood nor so easily accomplished. In fact, there is no problem in sewage disposal more puzzling than the question why one septic tank succeeds and another fails. Assuming that the tank is so designed as to retain the solid matters, the answer to the problem will be largely found in deciding the proper length of time to allow the liquid portion of the sewage to remain in the tank. In some cases it has been found that a period as short as four hours gives the best results, while in other cases over 24 hours has been considered essential. To determine the proper period for any given tank requires careful watching of the tank, measurements of the quantity of flow, temperature and strength of the sewage, etc., for a considerable time. Even after the tank has been adjusted to give good results, the task is not ended, because the temperature, quantity and strength of the sewage vary, and adjustment of the tank is occasionally needed to secure the best results. Fortunately, considerable variation is allowable in the conditions of the sewage, so that constant adjustment of the tank is not required. In the following pages, suggestions are made which will be of help in deciding whether the period of flow through the tank is too rapid or too slow. This period, which is usually called the *rest period* in the tank, is computed by dividing the capacity of the tank by the average discharge of sewage per hour.

When a new or cleaned tank is first put into operation, the septic action is very weak. It must be remembered that this action is caused primarily by the anaerobic bacteria and that they do not become active until most of the air or oxygen in the fresh sewage has been used up. Fresh sewage entering a tank in which the rest period is only a few hours may therefore pass out again before any considerable action by the anaerobic bacteria has taken place. But the solid matters retained in the tank, either floating or as sediment, will serve as breeding ground for the anaerobic bacteria, which in course of time will develop in immense numbers, and the true septic action will then be established. The time required for this to be accomplished depends principally upon the temperature of the sewage, although the composition of the sewage is a factor of some importance. In warm weather the growth of bacteria is greatly accelerated and their action hastened. Assuming that the first pronounced and continued ebullition of gas in a septic tank is a reliable indication of the establishment of septic action, the following tabulated statement will give some idea of this question as observed during the tests at the experimental station at Columbus, Ohio.

TABLE I.

TIME REQUIRED FOR SEPTIC ACTION TO BECOME ESTABLISHED.

Tank.	Regular operation began 1904-5.	Number of days before gas evolution was noted.	Temperature of sewage during period.
A	September 3	8	71° Fahr.
B	September 2	8	71° "
C	November 22	11	57° "
D	February 18	15	46° "
E	March 4	17	49° "

FORMATION OF SCUM

The gas, which is here suggested as an indication of septic action, is liberated by the action of the bacteria on the impurities in the sewage and principally on the solid sediment at the bottom of the tank. As the bubbles of gas rise to the surface, they at times carry masses of previously deposited sediment, or of sediment still in suspension, to the surface of the sewage where the sediment is held by the buoyancy of the gas or by adhering to other floating matter until gradually a film or coating of scum is formed. These actions continue until the scum attains considerable thickness. A septic tank in good working condition usually has from four to eight inches of thick scum over its entire surface.

The presence of a scum is not essential to the operation of a tank, the character of ordinary sewage being such that air and light will not penetrate to any distance beneath its surface. When a scum of moderate depth is present, the effectiveness of the tank is doubtless increased owing to the fact that under these conditions the bacterial action can go on closer to the surface. In the case of the experimental septic tanks at Columbus, Ohio, a well defined scum formed in no instances on the surface of any of the septic tanks, although during periods of unusual gas ebullition quantities of sludge would be brought to the surface and a spongy mat several inches thick thus formed. In all cases this mat slowly broke up and again fell to the bottom of the tank within a few days after its appearance.

Whether a scum will form on a septic tank is somewhat difficult to foretell in the case of a new plant. The chief factor in determining its formation is, probably, the relative strength of the sewage, which is dependent upon the per capita flow. A highly diluted sewage, especially where a large amount of surface water is included, generally carries suspended matters of such a nature that they tend to form in flakes which subside rapidly to the bottom. When such sediment is carried by gas bubbles to the surface of weak sewage, it generally falls back again to the bottom before a permanent scum has had an opportunity to be formed. Strong sewage, on the other hand, contains a relatively large proportion of colloidal suspended matters which have the nature of glue or jelly and which, therefore, readily stick together and form tenacious films over the bubbles of gas, thereby being kept on the surface.

Under some conditions, the scum forms to an excessive thickness, in some instances as great as two or three feet, and so solid as to bear the weight of a man. Such an excessive accumulation of scum is an indication that the solid matter is entering the tank at a greater rate than it is being liquified by the bacteria. This may be due to several causes which will be discussed in connection with the accumulation of sludge. It is believed that when a septic tank has its rest period properly adjusted to the strength, quantity and temperature of the sewage flowing into it, the scum will accumulate only very gradually after the first few inches are formed, and in some cases may remain at a practically constant thickness.

Formation of Sludge

The sediment accumulated on the bottom of the tank is composed of mineral matter, such as grit from road washings, and organic matter such as faeces, kitchen wastes, etc. The mineral matter is not acted upon in the tank to any appreciable extent, and therefore accumulates gradually, the rate depending on the lack of care taken to exclude such matters from the sewers. Of the organic matters, some are much more easily reduced than others. Thus cellulose, which is the chief constituent of the cell walls of vegetable matter and is largely used in the manufacture of paper, is very hard to decompose. If a large amount of such matters are brought into the tank by the sewage, they are likely to accumulate faster than the bacteria can liquify them. In fact, experience has shown that, in most septic tanks, as operated, such matters do accumulate as sludge at a fairly rapid rate, but the fact that in a few cases the depth of sludge has remained practically constant, at only a few inches, leads to the conclusion that, in the case of a sewage carrying no suspended mineral matter and only a small percentage of resistant organic matter, sludge will not increase in depth if the rest period in the tank is adjusted to the strength, quantity and temperature of the sewage, and furthermore that even when mineral and resistant organic matter are present in considerable quantities, the accumulation of sludge can be kept at a minimum rate by proper adjustment of the rest period. It must be remembered, in computing the rest period, that the sludge and scum reduce the effective capacity of the tank by the amount of their combined thickness, and that the rest period of a tank in operation should be calculated by dividing the hourly flow into the product of the horizontal area of the tank and the depth of liquid, deducting the thickness of scum and sludge.

The apparatus used at Columbus, Ohio, for measuring the deposit in a septic tank, while in operation, consisted of a glass tube 2.5 feet long and 0.5 inch in diameter, open at both ends and fastened parallel to the side of a wooden rod 12 feet long. Through the glass tube a fine wire was drawn, at the lower end of which was fastened a flexible rubber stopper, the smaller end uppermost. The wire extended up through the glass tube to the top of the wooden pole being guided here and there by screw-eyes.

In making a measurement, the rod was lowered into the liquid in the tank, and slowly inserted into the deposit on the bottom. After sufficient time had been allowed for displacement in the tube, the wire was pulled, drawing the rubber stopper into the lower end of the glass tube. The rod was drawn up, and the depth of the sludge in the tube measured.

This method is stated to give results about ten per cent. less than those obtained by carefully draining off the liquid and measuring the depth of sludge remaining on the bottom of the tank.

Excessive Accumulation of Scum and Sludge

The excessive accumulation of scum and sludge may be traced to several causes:

First. The tank may be overloaded, which means that organic matter is being brought into the tank faster than the bacteria can act upon it, and which corresponds to too short a rest period. In such a case, the sediment deposited at one moment is soon covered over with a layer of new sediment and the bacteria in the sewage do not have an opportunity to attack the lower layers. The best results seem to be obtained when the sediment is deposited in a thin layer and there exposed for some time. This requires an extensive surface for the deposition of the sediment, and this has been sought to be obtained in a patented tank by having the sewage flow over several shelves instead of over only one bottom, thus reducing the size of tank for the same horizontal area exposed.

Second. The rest period may be too long. Reference has been made to the production of enzymes by the bacteria. If the bacterial action is prolonged too far, these products of bacterial life may accumulate to such an extent as to interfere with the bacterial action, just as the activity of a crowd of persons would cease if they were compelled to breathe, for any length of time, the same air, which would contain the poisonous products from their lungs. In addition to the diminished activity of the bacteria due to this cause, some of these enzymes act chemically or physically on mineral matters in solution in the sewage causing them to precipitate, thus forming a new source of sludge, known as secondary sludge, just as in the older chemical process of purification, lime or other chemicals were added to the sewage to purposely cause a precipitation of such matters. With the septic process, it is desired to keep such matters in solution and thus simplify the problem of handling sludge.

Third. There may be an undue amount of mineral or resistant organic matter reaching the plant, from road washings or from manufacturing establishments, such as breweries, pulp mills, etc. The remedy in such a case is obvious.

Fourth. Chemicals entering the sewers from manufacturing establishments may be of such a nature as to cause a precipitation of matter that would otherwise stay in solution, or they may sterilize the sewage so as to prevent bacterial action. An investigation of manufacturing wastes entering the sewers should be made. Those of an objectionable nature should be prohibited and the manufacturers required to treat them separately.

SUSPENDED MATTER IN EFFLUENT

In addition to the rapid accumulation of scum and sludge, an improper working of the tank is indicated by a large amount of suspended matter in the effluent of the tank. Septic tanks, operating normally, effect a removal of about 50 per cent of the suspended matter of the crude sewage, with the resulting liquification of from 25 to 50 per cent. of the deposited sludge. Undue accumulation of sludge is undesirable only on account of the expense and inconvenience of removing and disposing of it and because it reduces the effective capacity of the tank. The presence of excessive amounts of solid matter in the effluent is, however, a more serious matter, for it indicates that the principal object of the septic tank, namely, the removal of solid matters, has not been attained. If solids are permitted to leave the tank with the effluent, they will clog filters or discolor water courses into which the effluent may be discharged. The presence of solids in the effluent may be due to:

First. Improper design of the septic tank, on account of which the sewage may enter it violently causing a disturbed condition of flow through the tank and preventing the settling of the solids in the sewage.

Second. Too short a rest period, not allowing time for the finer particles to settle, or for bacterial action to break down the solids.

Third. The precipitation of soluble matter by enzymes or other means, as before explained, from the clear sewage, on account of too long a stay in the tank. Such precipitated matters are usually black and of a colloid or jelly-like nature, difficult to treat in filters and hence especially undesirable to have in the effluent. They are usually of a density so nearly that of water that their sedimentation is slow and difficult to effect, so that large quantities are carried out in the effluent.

Fourth. The upheaval of masses of previously settled matter, by relatively large quantities of gas. The action of the bacteria is usually decreased by the low temperature of the sewage during the winter, and during this season the sludge is likely to accumulate faster than the average rate. In the spring, as the temperature rises and bacterial activity increases, gas is produced in the lower layers of undigested sludge. This gas will accumulate until its buoyancy is great enough to enable it to break through the layers of sediment above it. This it does suddenly, thereby agitating the sewage in the tank, preventing sedimentation and even diffusing large amounts of previously deposited sediment through the sewage. This feature in the operation of septic tanks, which is so detrimental to filters through which the effluent may afterward be passed, is an entirely normal one and may be considered inevitable unless some means is taken to counteract it. Passing the sewage through a second tank, specially designed to effect sedimentation, in which active bacterial action is prevented by frequent removal of sludge, will remove a large percentage of the sediment. Passing the septic tank effluent through an anaerobic filter will also largely reduce the amount of suspended solids. This method is in use at the works of the Allis-Chalmers company at Milwaukee. There the anaerobic filter removes about 30 per cent. of the solids entering it from the septic tank, as shown by the average of the five analyses given in Table 7, page 86. It might be possible also to occasionally gently stir the sediment and thus liberate the gases in smaller quantities, especially if the tanks could be arranged to be operated intermittently.

Odors in Septic Tank

Still another indication of improper working of a septic tank is the presence of decided or nauseating odors. When operating properly, the odor in a covered tank resembles that of freshly turned soil and is not disagreeable, and outside the tank hardly any odor is perceptible at all, but when out of order, vile odors are produced which are carried by wind to considerable distances. Fresh sewage has not a strong odor, but septic tank effluent always has more or less. An effluent which is producing a marked odor of sulphuretted hydrogen (the odor of rotten eggs) has usually been too long in the septic tank, and as before pointed out, such an effluent is hard to treat in filters. Odors are caused, too, by the sudden liberation of gas, mentioned as occurring more frequently in the spring of the year, carrying partially decomposed sediment to the surface and exposing it to the air. The gas itself is not especially disagreeable.

An additional test of the efficiency of a septic tank may be made by determining the length of time that a sample of the effluent will keep, in a stoppered bottle, without putrefying. This test is called the putrescibility test and the method of making it is described in detail on pages 70–72. Effluent from a properly working septic tank should not putrefy in less than four or five days, on an average.

Indications of Successful Operation

The information gained from frequent observations of the rate of accumulation of scum and sludge, the quantity and nature of sediment in the effluent, the odors about the tank and the test for putrescibility may be used as indications of the success of operation of septic tanks. Chemical analyses also throw much light on the operations going on in the tank, but they are difficult and slow to make and are not required for an intelligent operation of the tank. In addition to the above points, note should be made of the variations in quantity and temperature and, so far as possible, of the strength of the sewage. Other things being equal, a warm sewage will require a shorter stay in the tank than a cold sewage, and assuming the temperature to be the same, a weak sewage requires shorter treatment than a strong sewage. Fortunately, these matters frequently adjust themselves fairly well, so far as seasonal variations are concerned; as the quantity of sewage increases in the summer, due to larger domestic use of water and leakage into the sewers owing to high level of the ground water, thus reducing the period of stay in the tank, the necessity for a longer stay is reduced by a lessening in the strength and an increase in the temperature of the sewage. Conditions are not always so favorable, however. At some places the strongest sewage occurs at the time of maximum flow. Yearly the amount and strength of the sewage will increase due to extensions of the sewer system and new connections to the sewers being made.

Removal of Sludge

The removal of the accumulated sludge from septic tanks is a task the difficulty of which depends on how the tank has been operated. In some instances, the sludge has been very foul and disagreeable to handle, but experience in many places proves that the removal of sludge from tanks is not generally attended with the production of a nuisance. In fact, the absence of odor in well-matured septic sludge is such as to cause comment. If, from any of the causes previously discussed, sediment is collecting faster than it is being reduced, the sludge will contain a large proportion of partially digested organic matter which will be very foul, but if the sludge is retained until it has passed through the putrefying stage and has actually become inert humus matter no nuisance will be created in its removal. This state is most likely to be arrived at near the close of the warm season during which bacterial action has been most active, and the fall of the year is hence the most advantageous time for cleaning the tanks. Some tanks, however, will require cleaning much oftener than once a year: some as often as once in six weeks.

THE OPERATION OF GRIT CHAMBERS

Grit chambers should be drained and the sludge removed whenever the evolution of gas therein becomes prominent, the reason for this being that soon after the evolution of gas begins actively a violent upheaval of the sludge deposit is likely to be caused by large quantities of the gas suddenly breaking through its upper layers. Such an occurrence would cause considerable quantities of sediment to be carried out in the effluent. It was found in the experiments at Columbus, Ohio, that it was necessary to clean the grit chamber about every eight or ten days. In cold weather a somewhat longer period between cleanings was allowable on account of less active fermentation during seasons of low temperature.

THE OPERATION OF SETTLING BASINS

Settling basins, like grit chambers, should be drained and cleaned at the first marked sign of gas evolution, otherwise septic action will become prominent and will interfere to some extent with the process of sedimentation, the tank being converted by this method of operation into a septic tank. At Columbus the periods between obligatory cleanings varied in a general way with the temperature of the air and of the sewage. The shortest periods were noted in June, 1905, being of about seven days' duration. The longest period was noted in December-January, and was of 37.71 days' duration. The average period between obligatory cleanings of Plain Settling Tank A, from August 16, 1904, to June 30, 1905, was 19.13 days. In the case of Plain Settling Tank B, which was operated from November 24, 1904, to April 18, 1905, the average period between obligatory cleanings amounted to 20.46 days. The period of flow in tank A was eight hours and in tank B six hours.

From the studies on these tanks the conclusion was reached that in practice the period of subsidence required for the removal of the maximum economical percentage of the suspended matter is longest when the strong sewage is under treatment. It seems to be sufficiently clear that during storm flows, the proportion of mineral to volatile suspended matter will be much higher than normally, and due to this fact the rate of subsidence of the particles of suspended matter will probably be greater, owing to their higher specific gravity. During the night period, say 4 P. M. to 12 P. M., the suspended matter contained in the crude sewage is only about one-half that of the day flow, 8 A. M. to 4 P. M. The rate at which the suspended matter in the weaker sewage subsides is much lower than that in the case of the strong day sewage, and after subsidence for a period of time sufficient for the removal of the economical percentage of the suspended matter in the day sewage, the residual amount of suspended matter in the weak sewage is less than that in the strong sewage, although the removal is much less.

THE OPERATION OF CONTACT FILTERS

Contact filter beds require constant and expert attention to secure successful operation. It is thought by some that the care required is greater than in the case of sand filters.

In some plants the dosing of the contact beds is controlled by hand operation of gates. In such a plant the manager is able to change the lengths of time of resting full and empty in accordance with the conditions of the sewage and bed and the temperature of the air, but such a plant requires the constant attention of the operator. To avoid the expense of such continuous service the majority of the plants have been supplied with automatic dosing devices of various types. The effect has been that such plants have received hardly any attention at all. Although these devices will reduce very largely the labor of operating a plant, they are not expected to do away with intelligent supervision. Almost every automatic device now available fixes the time of contact by the quantity of inflow, regardless of course, of the strength and temperature of sewage or condition of bed. They should be occasionally adjusted by the manager to suit changed conditions, and their operation should be frequently inspected. A slight leakage of the valves or siphons may altogether defeat the operation of the beds.

As generally operated, the bed is filled with sewage nearly to the surface of the filtering material, the operation usually consuming about half an hour, after which the bed is left resting full for two hours. The emptying requires about half an hour after which the bed is left resting empty for aeration for three hours. The whole operation of filling, resting full, emptying and resting empty, therefore, requires about six hours, allowing four fillings per day. In some cases the time has been cut down to shorter periods, but in other cases, as for strong sewage, the time is lengthened out to eight hours, allowing only three fillings per day. The length of time which is proper to leave the sewage in contact with the filtering material depends on a number of conditions such as the character of the sewage to be treated, the amount and fineness of the solid matter in suspension in the sewage, the temperature of the air and sewage, and the fineness of the grain of the filter; and these conditions also affect the length of time necessary for proper aeration of the filter. When the air is cold, the bed and its bacterial content become chilled while resting empty and the activity of the bacteria is thereby greatly reduced. so that under these conditions a longer time would be required for their complete action when the bed is filled than if a higher temperature existed. The same effect would be caused by a lowering of the temperature of the sewage. such as normally occurs every winter.

Winter Operation

The operation of contact filters in high latitudes may give trouble during severe winter weather by the freezing of the surface layers, thereby preventing perfect aeration, but there is very little information available on this point at the present time. During the tests of contact filters at Columbus, Ohio, there was no apparent effect on their efficiency due to the cold weather of 1904–05 when ice formed on the surface of the filters and remained there practically all winter. In no case, however, were the surfaces of the filters completely covered with ice, nor were the surface layers of the filtering material ever completely frozen. The minimum temperature recorded during the test was 7 degrees below zero Fahr. Where lower temperatures occur and danger of the complete sealing of the surface by ice is feared, some of the methods to be described under the heading of "operation of percolating filters" may be adopted.

Clogging of Contact Beds

Under some conditions the sewage bacteria develop in such large numbers as to cause a considerable clogging of the pores of the filter. and other growths of vegetable matter may have the same effect. The solid matters in the sewage also gradually clog the bed by being retained in it. As the clogging, due to either or all of these causes. progresses the difficulty of securing satisfactory aeration increases, because of the imperfect circulation of air in the clogged passages and the fact that the oxygen is quickly consumed from the air by the impurities in the filter. When such conditions obtain, a longer period of resting empty is required.

When the pores of the bed are clogged to a large extent and the period of aeration is too short, the action that goes on in the contact bed is more nearly like that occurring in an anaerobic filter. That is, the conditions are suitable for the development and action of the anaerobic bacteria, so that there may be a reduction, by liquefaction, of the amount of solid impurities stored in the filter, but there will be little effect upon the matter in solution. Inasmuch as the beds are designed, primarily, for the oxidation of the impurities in solution, it is generally considered best to use some preliminary treatment to postpone as long as possible the time when the beds will become clogged. Such a condition is more likely to occur where crude sewage is applied to the beds than where some preliminary treatment is used to reduce the amount of solid matter which the beds have to dispose of, but when the preliminary treatment consists of passage through a septic tank, the operation of the latter must be carefully watched in order to prevent the discharge into the beds of large amounts of finely divided suspended matter, such as occurs during periods of violent ebullition of gas in the tank.

Another disadvantage of the clogging of contact beds lies in the reduced capacity of the beds. Naturally, as the pores of the filter become filled with solid matter, the amount of sewage that can be flowed in is correspondingly reduced, and, therefore, for a given flow of sewage a larger number of contact beds will be required or a shorter period of storage, which would result in poorer purification. The clogging of contact beds is the principal cause of expense in operation, for when the clogging becomes serious the material of the filter must be cleaned or washed, and perhaps rehandled. In rehandling the material, there is always considerable loss due to crumbling of the particles, and this loss must be replaced by fresh material. The cost of treating sewage at Manchester, England, by contact beds, increased from about 12 cents to about 23 cents per capita during the five years beginning with 1903–04, and this increase is stated to be largely due to renewals of contact bed material during the last two or three years. The material used there was soft furnace clinkers. It is not definitely settled, as yet, whether clogging will occur in all contact beds; there may be locations where the conditions are such as to maintain a balance between the amount of solids entering the bed and the amount liquified or carried out, but in the great majority of cases a gradual clogging does occur.

EFFICIENCY OF CONTACT BEDS

The degree of purification effected by contact beds is not so high as in the case of sand filters. When the beds are filled as well as emptied through drains laid in the bottom, it is clear that the sewage entering last does not receive as thorough treatment as that first entering, for two reasons. First, it remains in the bed a shorter time, by about one hour, being the first out as well as last in. Second, the sewage first in in rising through the filter robs it of its air supply and receives the most vigorous action of the bacteria, the later sewage coming in contact only with bacteria which have already spent their energy on the sewage first in. To improve the purification of the sewage where contact beds are used, a large number of plants are so arranged that the sewage can be passed successively through two or three beds, the last usually being of finer grain than the first. The sewage last in and first out of the first bed would then be the first in and last out of the second bed, thus averaging up the treatment and giving all a more thorough contact. It has been found in some cases that there is more economy of filter area in passing the sewage successively through two beds than in obtaining the same degree of purification by long storage in a single bed.

To gain an accurate idea of the effectiveness of the beds, samples of the sewage first leaving and last leaving the bed should be collected occasionally and tested for putrescibility as described on a later page.

THE OPERATION OF PERCOLATING FILTERS

NORMAL OPERATION

Percolating filters, like contact filters, are operated intermittently so as to afford opportunity for aeration. During the aerating period, the sewage is retained in the dosing chambers until a sufficient quantity has accumulated to flood the bed to the required depth, when it is discharged onto the bed by automatic devices, or by hand-operated gates. Dosing tanks generally have a capacity such that when discharged the dose of sewage will cover the filter to a depth of three to four inches. When sand filters are properly cared for, a dose of this size disappears into the sand in from one-half to two hours, the rate depending principally on the fineness of the sand. Under some conditions much larger doses may be applied, as will be pointed out later. In the Columbus experiments with percolating filters the sewage was applied in one dose per day, in all cases where the filters were operated at a rate of less than about 500,000 gallons per acre in 24 hours. The hour of application was kept about the same for a period of 14 consecutive days. The hour of dosing was then moved ahead four hours, with the view to making each filter in the long run receive sewage corresponding to the average composition for the 24 hours of the day, and thus preventing some beds from always receiving strong day sewage and others the weak night sewage. The doses of sewage were flowed onto the surface through troughs, or pipes, so arranged as to distribute the sewage evenly and quickly, but without disturbing the surface of the filtering material.

During ordinary conditions of operation, the surface of the filter should be smooth and level as shown in the view of the Wauwatosa filters in Fig. 9.

The efficiency of filters may be increased somewhat by aerating the influent sewage, especially that which has passed through a preparatory treatment, such as the septic tank, where it has been deprived of practically all dissolved oxygen. At Saratoga, N. Y., Barbour made tests which showed that the sewage leaving

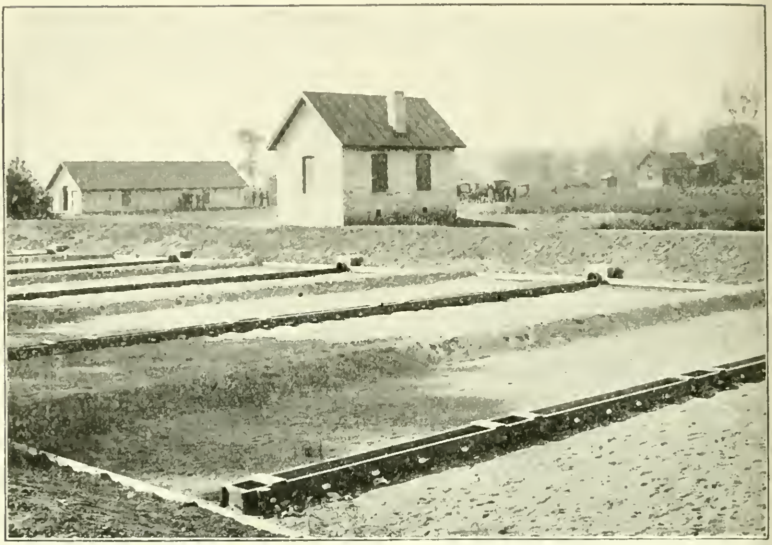


Figure 9.—Percolating Filters at Wauwatosa, Wis.

the septic tank contained practically no oxygen, but after passing the aerating device forming part of the purification plant, it contained over 70 per cent. of the total amount possible for it to absorb. If the sewage had been applied directly to the filters from the tank, it is reasonable to believe that as thorough oxidation would not have been secured as with the additional supply of oxygen supplied by aeration.

Clogging of Surface

As previously mentioned, considerable straining action goes on at the surface of filters of this type, the solid matters being retained there owing to their inability to pass through the small pores of the filter, which is usually composed of sand, and also to the fact that they adhere to the particles of filter material and their coats of bacterial growth. The retention of these solids results in the gradual clogging of the surface so that an increased time is required to pass the dose through. The nature of the material collected at the surface of the filter varies with the nature of the sewage applied, in some cases the larger portion being gritty or of a silt-like nature, while in other cases it contains more colloid or jelly like material, while in still other cases considerable fibrous material is present.

FORMATION OF MAT

Under some conditions, as when the sewage contains considerable amounts of sulphuretted hydrogen, a thick blanket-like growth may form on the surface of the filter. Where there is much colloid or fibrous material deposited, it forms a sort of woven mat or crust on the surface of the filter. After the dose of sewage has passed through the filter and while it is aerating, the crust tends to dry, weather conditions permitting, and if it has attained a sufficient thickness it will shrink and crack and usually curl or lift from the filter surface. The suspended matter of subsequent doses undoubtedly reaches the filter surface through the cracks in the mat, to a considerable extent, but in the main the mat forms a very complete covering intercepting most of the suspended matter.

Care of Surface of Filters. When a mat of this sort has become so dense as to retard the filtration greatly, it is necessary to remove it. It may often be peeled off without the removal of a very material amount of sand if it is fairly dry. A mat of this sort is shown in Fig. 10. If the mat is not tough enough to be removed in this way, it may be raked into piles and after the piles have grown by successive rakings to a considerable size they shoult be removed from the bed. Great care should be taken to prevent the mixing of any of this material with the sand.

A tough mat of this sort rarely forms when the sewage which is applied to the filters has been thoroughly settled, either in a sedimentation basin or septic tank, owing to the small amount of fibrous matter carried by the sewage that reaches the filter. The fine sediment in suspension is, therefore, able to penetrate into the upper layers of the filter instead of being held on the surface by a mat. When the filter becomes clogged by material of this sort, it should be removed by scraping off the thin layer of silt. When in this condition, the surface of the filter does not dry out readily, so that it is generally removed in a damp condition and usually a larger proportion of sand

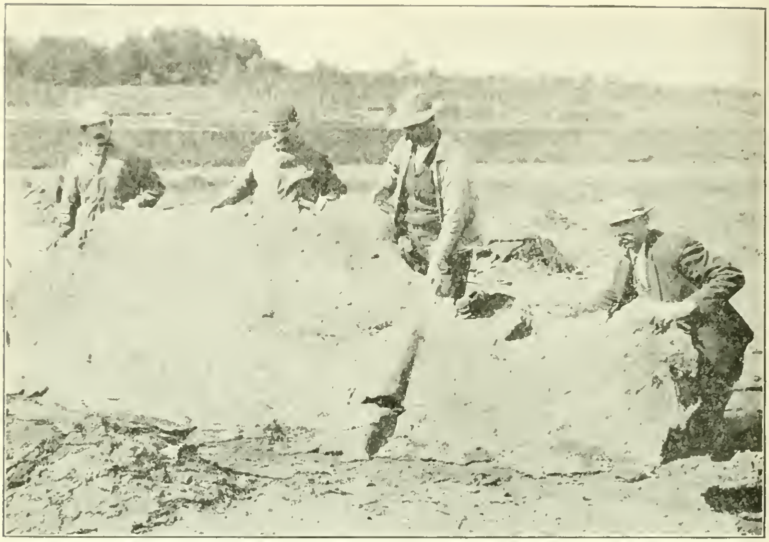


FIGURE 10.—SEWAGE MAT FORMED ON PERCOLATING FILTERS AT WORCESTER, MASS.

is present in the removed material than when a mat is removed.

In some instances instead of removing the material causing the clogging, the managers of the works have simply raked or harrowed the surface of the filter. This breaks up any mat that may have formed and loosens the upper clogged layers of the filter material allowing the sewage to pass through the filter at a high rate, but the relief is only temporary and gradually the upper part of the filter becomes so filled with fine silt that the capacity of the filter cannot be maintained normal even by very frequent raking or harrowing, and it is necessary to remove a considerable depth of filter, taking a large amount of the filter material along with the accumulated silt and organic matter. Where suitable filter material is not readily obtainable, the expense of replacing that lost in this way will more than offset any temporary saving effected by harrowing.

For breaking up the surface crust and gathering into piles for removal a hand rake is generally used. The rake may also be used for loosening the clean sand for a depth of one to two inches. A wire-tooth horse weeder is preferable for this purpose, however.

After removing the crust and upper layer of dirty filter material, it is usually desirable to loosen the upper part of the remaining clean material by harrowing it, on account of the reduced capacity caused by settlement and compacting of the sand by the action of the sewage passing through and by walking on the surface of the bed.

Better results are obtained by regular and frequent scraping and loosening of the material than by waiting until the operation of the filter is so interfered with as to compel cleaning.

When new material is added to bring the filter to its normal depth, after removal of dirty material, the new material should be plowed into the old and thoroughly mixed with it; otherwise clogging is likely to occur at the plane of separation between the old compacted material and the new loose material.

When beds have become clogged to a considerable depth by the storing of organic matter, such as may occur by operation at too high a rate, a very considerable reduction of such stored matter may be effected by resting the beds; that is, by not applying any sewage for a limited period. In order to prevent the drying out of the filter, with the consequent destruction of the aerobic bacteria in it, a bed resting or out of commission should have a small quantity of sewage applied to it at least twice a week.

The use of filter effluent for mixing with the sewage applied to filters has been suggested as having some advantages. Such effluent contains a considerable quantity of oxygen, in the form of nitrates, which is readily used by the aerobic bacteria in oxidizing the impurities in the sewage. The use of filter effluent in this way would generally require pumping and might not be economical, but its occasional use in the case of a bed clogged with organic matter is worthy of consideration.

Worms and burrowing animals occasionally give trouble by opening passages in the sand by which unpurified sewage reaches the drains. Folwell states that these have been driven out by flooding once or twice with strong or septic sewage.

Cost of Cleaning Sand Filters. The period between cleanings which will be most economical at any plant must be found by experiment. It will depend upon the nature of the sewage, the fineness of the filter material the cost of labor, methods and apparatus used, and other factors. If unsettled, crude sewage is applied, it will be necessary to clean the beds more frequently than in the case of settled sewage.

At Worcester, Mass., it was found necessary to rake over portions of the beds treating unsettled sewage as often as once in two weeks, and the quantity of refuse removed amounted to about 14 cubic yards per million gallons of sewage treated, the expense of removal amounting to $13 per million gallons. The Worcester sewage contains considerable manufacturing wastes and the expense of treating it is, on that account, probably higher than the average. Venable states that the cost of raking and removing, from sand filters, sludge deposited by crude sewage in various towns in Massachusetts ranges from $3 to $11 per million gallons of sewage, or from 12 cents to 30 cents per capita per annum.

At the Lake Forest, Ill., plant it was at first necessary to rake over the entire filter area twice a week, the beds receiving two doses per day, but after the better regulation of the septic tanks, resulting in less suspended matter reaching the beds, a great improvement was seen in the amount of care which the beds had to receive. These beds consist of a fine sand and normally require about ten to twelve hours of labor per week to keep them in good condition. Where coarser sand is used in the beds, less labor is required to maintain an efficient rate of filtration.

Winter Operation of Percolating Filters

The operation of percolating filters during the winter months is likely to give some difficulty in high latitudes on account of the accumulation of ice and snow, but such operation is perfectly feasible, although more care and greater judgment are required than for operation at warm temperature. An instance is recorded where sand filters were successfully operated during a winter when the average minimum daily temperature of the air at the plant during the months of December, January and

February was 9.3 degrees above zero: in February alone it was only 4.8 degrees above, and during the winter there were 28 days of zero weather, with a minimum temperature of 32 degrees below zero.

The sewage reaching the works usually has a temperature considerably higher than the freezing point of water. At Columbus, Ohio, the minimum average temperature of the sewage during 1904–05 was 39° Fahr., while the minimum air temperature was minus 7°. At Brockton, Mass., a temperature of 44° was recorded in the sewage. At Boston, Mass., the average temperature of the crude sewage during the winter quarter of 1906 was 43° and of 1907 42° Fahr.

The time required for filtering the sewage is usually not so great as to give opportunity to cool it if some simple precautions are taken to prevent its unnecessary chilling. Furthermore, the process of oxidation effected by the anaerobic bacteria in the filters gives rise to heat which tends to counteract the cooling effect of the air. In flooding beds in winter, one of the vital points is to cover them quickly and to a greater depth than in summer.

At Clinton, Mass., experience shows, as reported by Allardice, that when the air temperature is higher than 15° Fahr., the beds can be satisfactorily operated in their normal, flat condition by applying the sewage in large doses of 250,000 gallons per acre, sufficient to cover it about nine inches deep. When there is deep snow on the bed this method is not satisfactory as the snow chills the sewage too rapidly and ice forms on the beds even when furrows are plowed in the snow so as to allow the sewage to reach the far points of the bed as quickly as possible.

Mr. Herbert F. Snow relates the following experience with sand filters at Brockton, Mass. "Considerable ice began to form around the edges of the level beds, and gradually to approach the carriers. The temperature of the sewage, at this time about 44 degrees Fahr., was readily chilled by the snow to a point where it had little power to melt the ice. Observations made while putting sewage into snow, showed the temperature to be: in the pipe 45° Fahr., 20 ft. away from the carrier, 43°; 50 ft. 42°; 75 ft. 37°; and beyond this the sewage did not penetrate the snow at all. Within this area the liquid retained in the upper inches of the filter by the accumulated organic matter froze solid. At a greater depth than 2 inches, less liquid being retained by the sand grains, though frozen, the mass remained porous.''

If the crust of ice and snow that forms on the top of the beds is light, the heat stored in the sewage is generally sufficient to melt it as each dose is applied, only the upper few inches of the beds freezing solid between doses.

If a solid sheet of ice is prevented from forming on the surface of the beds the frost will push the grains of sand on the surface, which are mixed more or less with organic matter, further apart, and this will let the water through more easily. Eddy, at Worcester, Mass., has taken advantage of this fact by giving the beds a dose of about 300,000 gallons per acre, equivalent to 11 inches in depth, and in that way has got rid of the frost and, in a day or two, of any accumulation of ice and snow that may have formed.

When the bed is flooded to a considerable depth, a sheet of ice will form, in cold weather, on the surface of the sewage before it has time to sink into the filter, and as the unfrozen sewage seeps away, the ice will be lowered into contact with the filter surface to which it will freeze, completely sealing the bed, unless some means are taken to prevent it. Various methods, more or less satisfactory, have been tried, some of which will be described

Formation of Ice Roof. The method in use in all the systems upon the drainage areas of the Metropolitan Water Supply of Boston, Mass., is to place stones about 6 inches in diameter at frequent intervals on the beds, then confine the sewage flow to one bed until a covering of ice is formed, which will be supported by the stones, as the sewage drains away through the bed, forming a roof of ice which will protect the bed from snow and keep subsequent doses of sewage warm, allowing them to filter in the coldest weather.

The same method is used by Eddy at Worcester, Mass., with the modification that instead of placing stones on the filters the sludge on their surface is raked, in the fall of the year, into piles about 6 inches high and approximately 12 inches in diameter, and about 8 feet from center to center, these piles serving to support the ice covering from contact with the filter surface. The sewage is distributed to these beds from four different points and practically no trouble had been experienced from ice freezing to the surface.

Use of Furrows. Another method that has been quite generally used, though not always with success, is to plow the beds into furrows, in the fall of the year just previous to the time when freezing takes place. The sewage is distributed over the beds in these furrows and on account of the greater depth in proportion to exposed area, it is not so likely to freeze as if spread out into a thin sheet over the entire bed. Fig. 11 shows this method of distribution in use at Brockton, Mass. Considerable variation in the size of furrows has been used by different persons. No doubt the nature of the sewage, as regards the amount of sediment it carries, the size of grain of the filter material, and other matters, have a bearing on the question as to what size of furrow is most advantageous. Little information of a definite nature is available on this point. Winslow reports that the beds at the Ohio State Reformatory at Mansfield, Ohio, are built of friable crushed sandstone. They were originally plowed with furrows 1.5 ft. high, and 4 ft. apart, but this worked badly, and the available area was unduly decreased and the beds froze. Later small furrows 6 inches high were plowed, giving poor results, the beds being half frozen and covered with slush. Probably a judicious mean might prove more favorable. Bolling prepares his sand filters for winter use with the tops of the ridges about 3 feet apart, and the furrows about 12 inches in depth. Allardice, at Clinton, uses furrows 3.5 feet apart and 15 inches deep.

After a bed is newly furrowed, material from the sides of the ridges will fall and be washed down into the bottom of the furrows when the first four or five doses are applied. To lessen this to a minimum, Bolling, in making the furrows, uses a common Ames No. 2, double-moldboard plow, with an extra iron form attached to the moldboard, which enables a deeper cut to be made, and the flaring edges round the shoulders of the ridges, leaving less loose material to fall or be washed down into the furrows.

A combination of the furrow and ice roof methods is used by Allardice. The furrowed beds are given doses which range from 500,000 gallons per acre upwards. The dose is sufficient to flood the bed to a depth of more than a foot above the ridges, and, before it has seeped away, a coating of ice some two inches in thickness will generally form, which will rest on the tops of the ridges when the sewage has disappeared, thus protecting the bottoms of the furrows, which, he states, have never become frozen.

In the spring of the year the sediment that collects in the bottom of the furrows has to be cleaned out and carted off. Where crude sewage is applied to the filters, the sediment may be from 4 to 6 inches deep in the furrows. Since the sediment is mixed with the sand or other filter material that has fallen from the ridges, there is more loss of this material when the beds are operated by the furrow method than when operated flat.

It is not necessary to furrow more than one-fourth of the beds. The flat beds may be operated whenever the temperature in the morning is above 15° Fahr. When lower temperatures prevail the sewage may be turned onto the furrowed filter area, which may be operated at the high rates mentioned for the short periods of extremely cold weather. Operating the filters at high rates in this way probably produces an effluent quite inferior to that produced by the beds operated at their normal rate, and on this account, as well as on account of the greater ease of cleaning and the saving of filter material, it would seem to be preferable to operate the beds flat under all conditions, protecting them when necessary by an ice roof supported by stones or otherwise.

Under some conditions of operation it becomes necessary to clean the filters during the cold season of the year. It is important, in such an event, to select a time when the temperature is suitable. When it remains close to 32° Fahr. the filter freezes only to a slight depth; practically no deeper than the bottom of the clogged layer of material, which can be rapidly removed, in the frozen condition, without removing any considerable amount of clean material. If, on the other hand, the temperature is much below 32° Fahr., the filters freeze several inches deep, causing the loss of much clean material, if cleaning is done while the filter is in the frozen condition. Ordinarily the silt does not penetrate far into the filter, one-quarter to one-half an inch usually being the depth of clogging.

THE OPERATION OF TRICKLING FILTERS

Normal Operation

In the operation of trickling filters it is of prime importance to secure uniform distribution of the sewage over the area of the filter and, for this purpose, a number of styles of nozzles, gravity distributors, troughs, and mechanical appliances have been devised and experimented with. If these devices do not accomplish this object, some portions of the filter will receive an overdose, while other parts are not doing their share of work of purification. The effect of an overdose may be indicated by the accumulation of black sludge in the upper part of the filter, and if this accumulates to a great extent, it will clog the filter, causing the applied sewage to stand in pools on the surface. Such a clogging and pooling will prevent proper aeration of the filter and thereby reduce its effectiveness. Ordinarily a trickling filter will satisfactorily purify sewage applied at the rate of 2,000,000 gallons per acre, or the sewage of about 20,000 persons. The amount any particular filter can purify will depend upon its depth, the size and nature of the material of which it is composed, the temperature of the air and sewage and the strength and character of the sewage. A study should be made by the manager of each plant to determine the proper rate at which to apply the sewage to his beds.

Trickling filters do not produce as clear effluent as percolating filters, or even as contact beds do. The pores of the filter are large enough to allow most all solid matter in the sewage to pass through, there being no straining action as in the case of percolating filters. The large amount of sediment in the effluent from a trickling filter causes the treated sewage to have a muddy appearance even though it is perfectly stable and free from odor, and where the effluent is to be turned into a body of clear water it is generally desirable to settle out the sediment in small sedimentation basins. It is found that this sediment is not offensive. The amount of sediment in the effluent from a trickling filter varies considerably with the seasons, but will average up slightly less than the sediment in the influent sewage. In the experimental plant at Boston it was found that the amount of solid matter was less in the effluent than in the applied sewage except in the second quarter of the year. In the second quarter of each year there was an enormous increase of solids in the effluent to a point in excess of the amount in the applied sewage. This means, of course, that the suspended solids of the sewage are ordinarily held on the bacterial films which cover the stones, while during the second quarter the accumulated material is washed out again into the effluent. The trickling filter thus automatically frees itself from suspended solids, after accumulation has taken place to a certain extent, and this action will tend to prevent a permanent clogging of the beds, such as occurs in other types of filters.

Resting a trickling filter appears to be detrimental to its action and unnecessary, and its operation should, therefore, be made as constant and uniform as possible. It has not yet been determined definitely whether this decrease of efficiency is due to injury of the bacteria in the filter by changed conditions or to the detachment of dried masses of bacteria, or to other causes.

In case the filtering material becomes clogged, considerable relief may be obtained by allowing the filter to dry out and thereafter applying sewage for a short time at high rates so as to aid in the detachment and removal of the clogging matters.

WINTER OPERATION

During cold weather the operation of the filters should not be stopped, as this would allow the entire mass to become chilled, causing a lowering in the activity of the bacteria it contains. It is more difficult and expensive to protect trickling filters from extreme cold than percolating filters. The sewage necessarily being sprinkled onto trickling filters is more exposed to chilling by the cold air than where it can be flowed onto beds in large quantities under a covering of ice. It is, however, quite possible to operate trickling filters in cold weather. The disposal plant at the Allis-Chalmers' Works in Milwaukee operates very satisfactorily during the entire year. There the filters are covered with a roof and are provided with removable sides, which are put up at the approach of cold weather and taken down again in the spring. The roof and sides serve to protect the filter from snow and from chilling winds. Experiments have been made at Boston, Mass., and at Columbus, O., on the operation of trickling filters without protection. At Boston during 1906–07 minimum temperatures fell below 5° Fahr. on fifteen different days and on twelve days the maximum temperature was under 20° Fahr. Yet ice and snow collected only at the outer edge and corners of the filters, leaving the main part of their surface clear. The condition of the Boston experimental beds at their worst is shown in Figures 12 and 13.

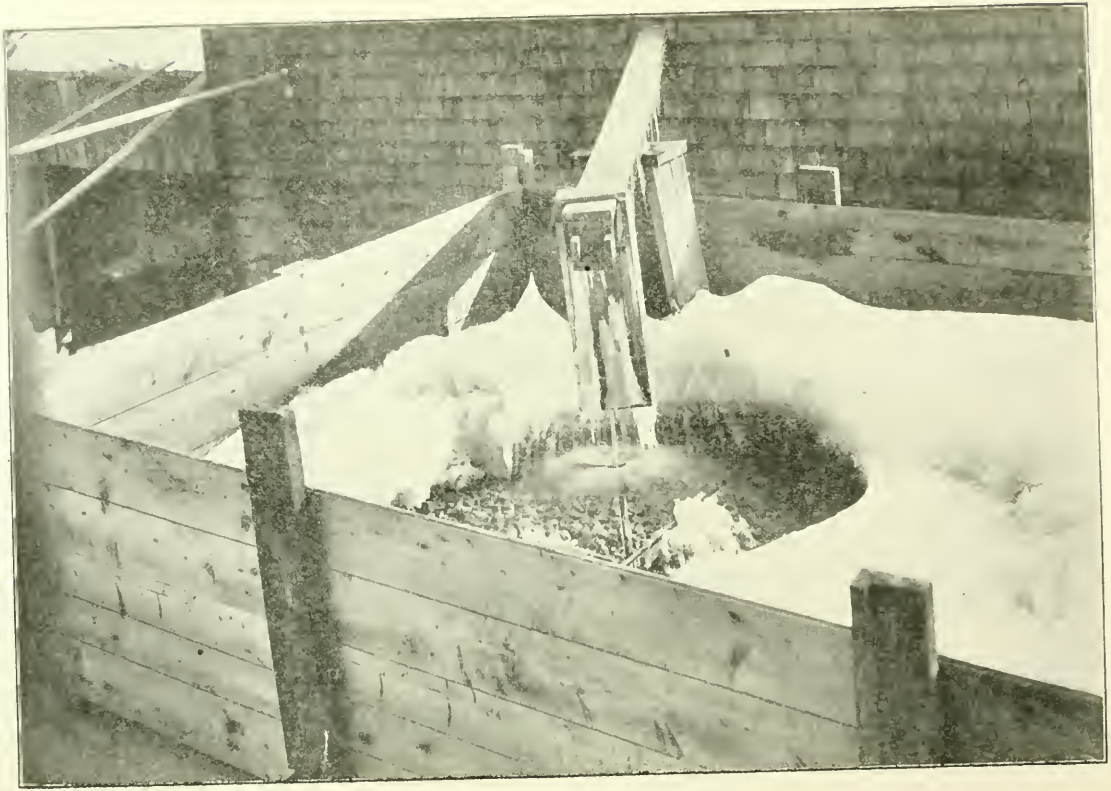


FIGURE 12.—GRAVITY DISTRIBUTOR UNDER SEVERE WINTER CONDITIONS.

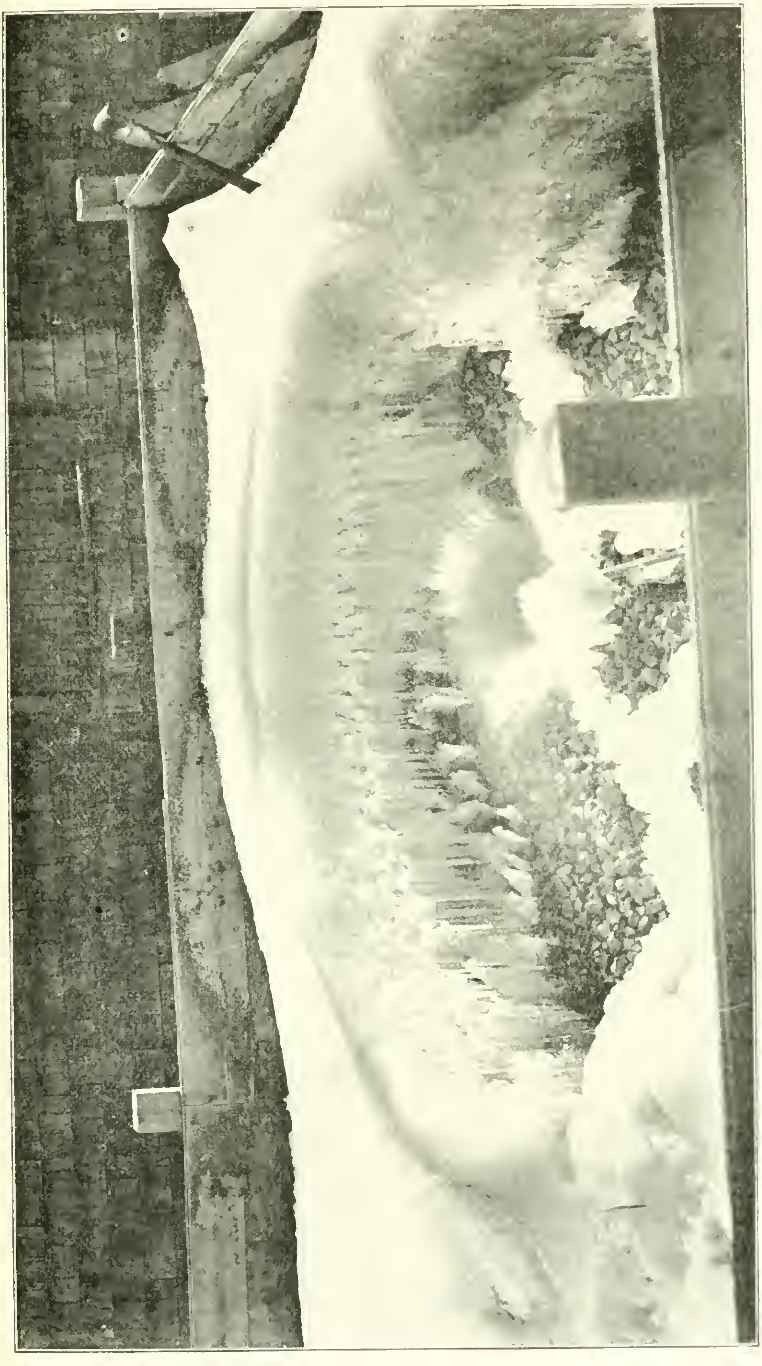


Figure 13.—Columbus Type of Sprinkler Under Severe Winter Conditions.

TESTS OF EFFICIENCY

The proper operation of purification plants does not require that chemical or bacterial analysis be made, for there are a number of manifestations by which one may judge of the efficiency of a plant. In addition to those which have already been discussed may be mentioned the test for putrescibility. This last has for its object the determination of the keeping qualities of the effluent. An effluent which has been so far purified as to contain no putrescible matter may be turned into any water course without danger of creating a nuisance, on the other hand, an effluent may still contain considerable of such matter but may at the same time contain a sufficient amount of dissolved air and mineral salts to oxidize it, and such an effluent would not putrefy if allowed to stand or if turned into a water course. If there is not enough oxygen in the sewage to completely effect this result, the effluent may, nevertheless, be considered satisfactory if it contains enough oxygen to prevent putrefaction for a reasonable length of time, for in that time the effluent will have become diluted with other water and will receive more oxygen from it to complete the work.

The test for putrescibility is made in different ways: two of which will be described. The first is called the odor test. In this method an average sample of the effluent, contained in a bottle which is completely filled and tightly stoppered, is placed where the temperature can be maintained practically constant, at 37° C. (or 98° Fahr.).

At the end of 48 hours the stopper should be removed and a test made for odor. If the sample gives off no offensive odor, nor is blackened, a non-putrescible effluent is indicated. If the odor is slight and disappears almost immediately upon removing the stopper the results are questionable. If the sample has blackened and gives off foul odors, the sample is putrescible and the degree of purification is unsatisfactory. In case it is not convenient to maintain a temperature of 98° Fahr., the same result may be obtained by keeping the sample at a temperature of 68° Fahr. but twice as long a time should be allowed before opening the bottle.

The second method is known as the methylene blue test. A small portion of an aqueous solution of the dye (1 cubic centimeter of a 1 per cent. solution) is added to the effluent in a glass stoppered bottle of 250 cubic centimeters capacity, and the sample is kept at either 98° or 68° Fahr. The blue color of the solution remains practically unchanged during the period of observation until the available oxygen in the effuent is used up by the organic matter present and putrefactive conditions arise. At this point the dye is reduced and decolorized. The time required for decolorization is a quantitative measure of the degree of putrescibility of the sample, and the retention of the color for a period of four days or more at 68° or of two days at 98° may be taken as an indication of good stability. Instead of the periods mentioned, some use a period of one week at 68° and four days at 98° as the standard. A higher degree of purification is required to satisfy this test than the test with shorter periods. A note should be made, in the records of tests, of the standard used.

The solution of methylene blue required in this test can be prepared by any druggist. The apparatus required for the test is simple and inexpensive and is shown in Fig. 14. It should be especially noted that the bottles must be completely filled with the sample, otherwise the air contained in the upper part of the bottle would help to oxydize the sample and make the test inaccurate.

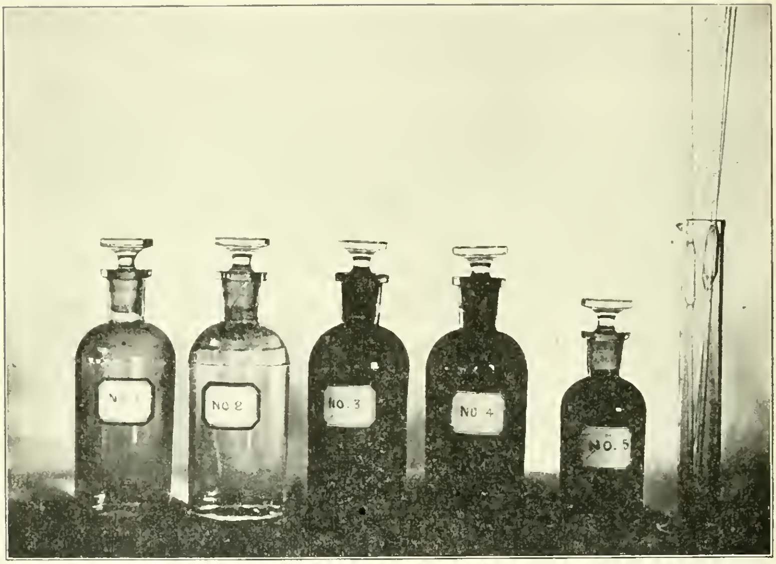


Figure 14.—Apparatus Required for Making the Putrescibility Test.

The large bottles each have a capacity of 250 cubic centimeters. One is needed for each sample to be tested. No. 1 and No. 2 show how the bottles appear when filled with crude sewage or effluent. The stock solution of methylene blue is contained in No. 5. By means of the pipettes, three of which are held in the graduate, 1 cubic centimeter of the methylene blue solution is measured and added to the samples in bottles 1 and 2. The resulting appearance is shown in Nos. 3 and 4. After the oxygen in the samples is used up the color disappears and the samples again appear like Nos. 1 and 2. Note that the bottles are completely filled up to the glass stoppers. The graduate is not needed in this test.

INVESTIGATION OF WISCONSIN PLANTS

During recent years there has been a good deal of discussion on the subject of the proper design of sewage purification plants, and there has been a large amount of investigation into the chemical and biological processes involved, both by experiments in laboratories and by means of miniature experimental installations. Interesting and valuable as these investigations have been, it has been realized that deductions drawn from them may not be strictly applicable to the cases of full sized plants operating under normal conditions.

As shown in Table 2, pages 74–75, there are now operating in the state of Wisconsin eighteen or more municipal and institutional sewage purification plants, their location being indicated on the map on page 76 by a circle; yet there is no published data to show what methods of operation or features of their designs are best adapted to Wisconsin conditions. There are also shown on the map, by black dots, the communities now having either complete or partial sewerage systems and discharging their crude sewage into the water courses. It is a matter of only a comparatively few years when practically all of these places, as well as others at present unsewered, will be compelled to purify their sewage.

It is evident that a careful study of this matter and the determination of the principles on which proper design and sound construction should rest may add materially to our information, increase the efficiency of operation and reduce the losses due to unnecessary or undesirable designs.

Reliable information concerning the operation of actual plants working under diverse conditions is difficult to procure on account of the neglect that befalls most plants.

The termination of the expert management of sewage purification plants usually takes place very shortly after their completion, for the engineer who designed the plant and supervised its construction and who has studied every phase of its environment, who knows what kind of sewage is to be dealt with and

TABLE NO. 2.

THE SEWERAGE OF WISCONSIN CITIES AND INSTITUTIONS.

Name of Place.	Population.	Disposal.	Method of Purification.
Antigo	5,000	Branch of Eau Claire River	None.
Appleton	17,000	Fox River	None.
Arcadia	1,500	Trempealeau River	None.
Ashland	13,000	Lake Superior	None.
Baraboo	5,800	Baraboo River	None.
Bayfield City	2,500	Lake Superior	None.
Beloit	15,000	Rock River	None.
Berlin	4,750	Fox River	None.
Beaver Dam	5,500	Beaver Dam River	None.
Burlingto	2,600	Fox River	None.
Chippewa Falls	12,000	Chippewa River	None.
Columbus	2,500	Rock River	None.
Dane County Poor Farm	300	Marsh drains into Sugar River	Septic tank and filter.
Delavan	2,500	Turtle Creek	None.
De Pere	4,500	Fox River	None.
Eau Claire	18,500	Chippewa River,	None.
Edgerton	2,300	Rock River	None.
Elkhorn	2,500	Marsh	Residential Septic Tanks.
Elroy	1,700	Baraboo River	None.
Fond du Lac	15,000	Fond du Lac River	Septic tank and contact beds; not in operation.
Ft. Atkinson	3,500	Rock River	None.
Hartford	3,000	Mill Pond and River	None.
Horicon	1,600	Rock River	None.
Janesville	14,000	Rock River	None.
Jefferson	3,500	Rock River	None.
Kaukanna	5,000	Fox River	None.
Kenosha	15,000	Lake Michigan	None.
Kiel	1,100		None.
Kilbourn	1,200	Wisconsin River	None.
La Crosse	33,000	Mississippi River	None.
La Farge	800	Kickapoo River	None.
Lake Mills	1,500	Rock Creek	None.
Lancaster	3,000	Creek emptying into Grant River	Septic tank and filters.
Madison	28,000	Yahara River	Septic tank and trickling filter.
Marshfield	6,250	Creek	Septic tank and filters.
Manitowoc	12,000	Manitowoc River	None.
Marinette	1,800	Menomonee River	Filters.
Mauston	2,000	Lemonweir River	None.
Mayville	2,000	Rock River	None.
Medford	3,500	Black River	None.
Menasha	6,000	Fox River	None.
Mendota Hospital	600	Lake Mendota	Septic tank and filters.
Merrillan	800	Branch of Black River	None.
Milwaukee	325,000	Milwaukee River	None.
Milwaukee County Institutions	2,000	Menominee River	Septic tank and filters.
Northern Hospital		Lake Winnebago	Septic tank and filters.
Menomonie	7,000	Red Cedar River	None.
Monroe	4,000	Sugar River	Septic tank and filters.
Mondovi	1,500	Buffalo River	None.
North Milwaukee	1,200	Mud Creek	Sedimentation tanks aeration and filters,
Neenah	6,000	Lake Winnebago	None.
Nekoosa	800	Wisconsin River	None.
Neillsville	2,500	Black River	None.
New London	3,500	Wolf River	None.
Oconomowoc	3,000	Branch of Rock River	None.
Omro	1,400	Fox River	None.
Oshkosh	30,000	Lake Winnebago and Fox and Wolf Rivers	None.
Phillips	2,000	Flambeau River	None.
Plymouth	3,500	Mullett River	None.

TABLE NO. 2

THE SEWERAGE OF WISCONSIN CITIES AND INSTITUTIONS—Continued.

Name of Place.	Population	Disposal.	Method of Purification.
Port Washington	4,000	Lake Michigan	None.
Prairie du Chien	2,500	Mississippi River	None.
Racine	35,000	Lake Michigan and Root River	None.
Reedsburg	3,000	Baraboo River	None.
Richland Center	2,500	Pine River	None.
River Falls	3,000	Kinnikinnic River	None.
Rhinelander	6,000	Wisconsin River	None.
Ripon	4,000	Silver Creek	Filters.
Sauk City	900	Wisconsin River	None.
Shawano	2,000	Wolf River	None.
Sheboygan	25,000	Lake Michigan	None.
Soldiers Home			Filters.
South Milwaukee	5,000	Lake Michigan	None.
Sparta	4,000	La Crosse River	None.
Stevens Point	11,000	Wisconsin River	None.
Stoughton	3,500	Yahara River	None.
Stanley	3,000	Eau Claire River	None.
Superior	35,000	Lake Superior	None.
Tomah	3,500	Branch of Lemonweir River	Septic tanks.
Tomahawk	3,000	Wisconsin River	None.
Two Rivers	5,200	North and South Twin Rivers	None.
Wales Sanitarium	200	Subsurface tile system	Septic tank.
Wauwatosa	3,000	Menominee River	Septic tank and sand filters.
Wausau	14,500	Wisconsin River	None.
Waukesha	8,000	Fox River	Septic tank.
Watertown	10,500	Rock River	None.
Waupun	3,000	Rock River	None.
West Salem	1,000	La Crosse River	Settling tank.

PLANS APPROVED BY THE STATE BOARD OF HEALTH.

Name of Place.	Population	Disposal.	Method of Purification.
Athens	900		Septic tank.
Ellsworth	1,100	On a meadow	None.
Menomonie Falls	900		Sedimentation tanks.
Phillips	1,800		
Waupaca	2,900	Waupaca River	Two septic tanks.
West Bend	2,100	Milwaukee River	Septic tanks.

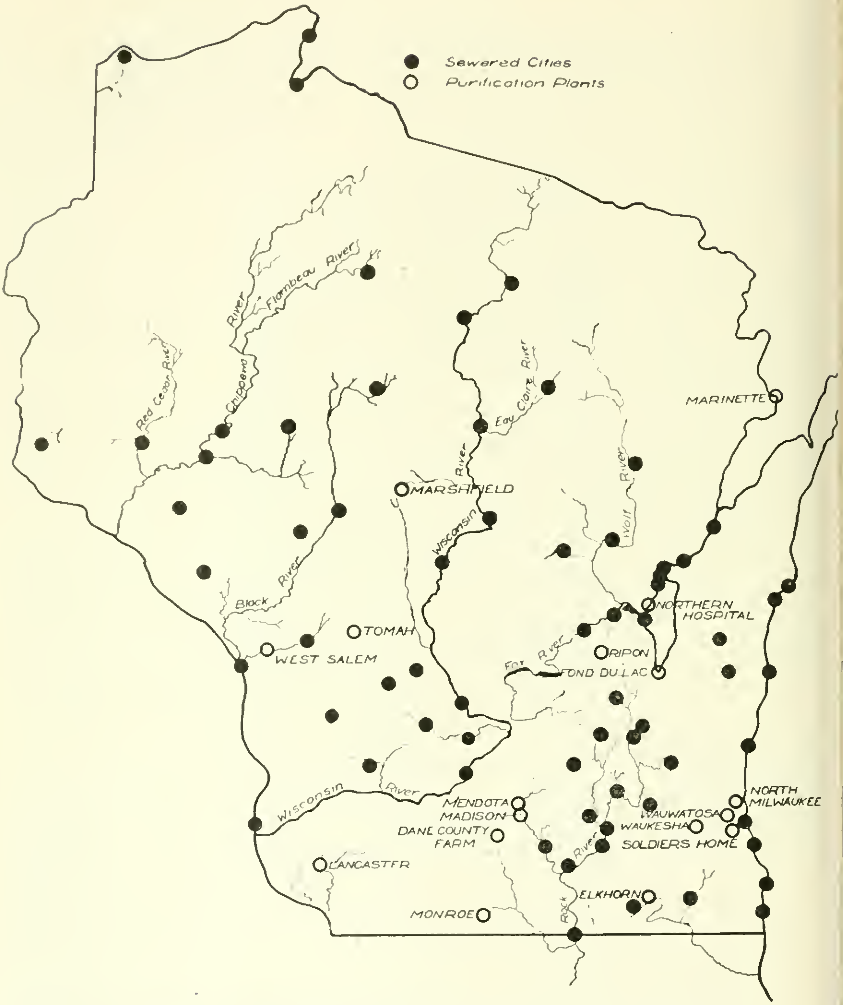


FIGURE 15.—MAP OF WISCONSIN SHOWING LOCATION OF PURIFICATION PLANTS

its quantity and variation, and who understands how such variations are to be met, leaves, and the completed plant is often turned over to the unwilling care of some city officer with other duties which already fill his time. Common imagination credits the plant as being a place of bad odor and revolting conditions. The idea that it can be a place of interest and source of information is not readily acquired. It follows that officers are not ordinarily found who like to be associated with it, or who take pride and interest in learning the principles of its construction and operation. Moreover, in most cases, the laudable desire on the part of city officials to limit the city expenditures, results in the narrowing down of appropriations for the care of the plants, to such an extent as to result in practical abandonment; or at best the operation is done in such a perfunctory manner as to be inefficient. The careful and patient observation required to study each phase and understand its cause is, therefore, not generally found among those entrusted with the care of plants.

In view of these facts it was decided, in 1907, to begin an investigation of the sewage purification plants in operation in the state of Wisconsin. By the cooperation of the College of Mechanics and Engineering and the College of Agriculture of the University of Wisconsin, and the State Hygienic Laboratory, sufficient funds were provided to pay the expenses incident to inspecting some of the plants, collecting and transporting samples and making analyses. The College of Agriculture was interested more particularly in the study of plants designed for the disposal of dairy wastes, while the funds of the Engineering College were directed to the study of municipal and institutional plants. The results of the latter study are given on the following pages.

PLANT AT MADISON

The study of the Wisconsin sewage disposal plants was started with the investigation of the city plant at Madison. This plant being near the laboratory afforded a better opportunity to study its workings, than some of the plants out of the city.

At the time when this study was commenced, in October, 1907, the septic tank had not been cleaned since early in July of the same year. In looking over the analyses in Table 3, an improvement in the action of the tank can be seen after it was again cleaned, in October, 1907. Just before being cleaned, it is found that the effluent from the tank was heavy in suspended solids and organic matter. As shown in Table 4, 3,600,000 gallons of sewage were pumped on October 8, 1907. At this rate of flow, the sewage remained only about two and one-half hours in the tank. This was too short a period to allow complete action, as is shown by the fact that the effluent putrefied in one and one-half days.

During the summer of 1908, better purification was obtained than during the previous summer. This fact was shown by a few analyses (not shown in the table) made during the summer of 1907, before active work on the study of this plant was begun. One reason for this was that the summer of 1908 was a very dry one, and the capacity of the tanks was not so greatly overtaxed as it is in rainy weather.

In Figure 16 is shown a graphical comparison of the chemical condition of the crude sewage with that of the effluent at the Madison Plant, based on averages for the year computed from Table 3. In the septic tank effluent there was an average removal of 42.8 per cent. of solids in suspension, 31.5 per cent. of chlorine, 44.6 per cent. free ammonia, 60.8 per cent. of albuminoid ammonia. The chlorine is always lower in the effluent of septic tanks than it is in the raw sewage. Apparent loss of chlorine during aeration is sometimes caused by the formation of chlorates. The per cent. of chlorine existing as chloride only was determined.

In perfectly fresh excreta, taking the solids and liquids together, the total nitrogen somewhat exceeds the chlorine. The ratio existing between the quantities of these two elements will remain unchanged when the excreta is diluted with pure water, so long as the nitrogen and chlorine remain in fixed forms. Therefore, the same ratio is generally applicable to fresh sewages. A decrease in the ratio indicates the gaseous dispersal of nitrogen or the addition of chlorine by diluting with impure water.

There was a removal of 44.6 per cent. of nitrogen as free am-

TABLE NO. 3.

SHOWING VARIATION IN QUALITY OF SEWAGE AND EFFLUENTS AT THE MADISON, WIS., MUNICIPAL PLANT.

The quantities given are monthly averages expressed in parts per million.

Date.	Sample.	Solids in suspension.		Free ammonia.	Alb. ammonia.	Nitrites.	Nitrates.	Chlorine.	Oxygen consumed.	Putrescibility point.	Amount of sewage in gal. per day.
		Total.	Fixed.								
1907. Oct.	Raw sewage	133.	35.	26.25	4.	0	0	89.2	60.2	½ day	
Oct.	Tank effluent	86.	16.	14.25	2.25	trace	0	51.2	17.1	1½ days.	2,004,000.
Oct.	Filter effluent	40.	14.	11.00	1.25	0	.5	46.8	7.0	5 days	
Nov.	Raw sewage	125.	46.	50.25	7.	0	0	94.8	73.6	6 hours.	
Nov.	Tank effluent	60.	17.	35.5	1.5	.8	0	56.2	25.6	3 days.	2,014,000.
Nov.	Filter effluent	53.	15.	18.00	0.75	0	1	52.7	6.4	7 days.	
Dec.	Raw sewage	127.	40.	45.00	29.	0	0	101.0	59.1	½ day.	
Dec.	Tank effluent	72.	24.	31.00	21.	0.5	0	50.1	19.2	3 days.	1,625,000.
1908. Jan*	Raw sewage	149.	60.	40.	25.	0	0	68.2	48.	½ day.	
Jan.	Tank effluent	77.	15.	23.	12.25	trace	0	54.0	11.	2 days.	1,512,000.
Feb.	Raw sewage	116.	34.	51.2	26.4	0	0	72.4	54.0	½ day.	
Feb.	Tank effluent	118.	31.	28.4	8.0	0	0	61.2	12.0	2 days.	1,842,000.
Mar.	Raw sewage	139.	46.	39.	24.6	0	0	59.4	48.	6 hours.	
Mar.	Tank effluent	105.	21.	25.2	7.8	trace	0	48.5	11.	2½ days	1,949,000.
April.	Raw sewage	145.	46.	46.1	28.2	0	0	62.5	52.1	½ day.	
April.	Tank effluent	52.	15.	28.1	7.	0	0	39.1	10.	3 days.	2,140,000.
May	Raw sewage	126.	34.	51.2	26.4	0	0	72.0	94.8	½ day.	
May	Tank effluent	96.	16.	26.3	5.0	0	0	59.	56.8	3 days.	2,855,000.
May	Filter effluent	40.	14.	10.	3.0	4.	2.	51.	10.2	7 days.	
June	Raw sewage	129.	24.	52.3	25.4	0	0	69.2	81.1	6 hours.	
June	Tank effluent	71.	18.	28.2	6.4	0	0	48.2	52.4	3 days.	3,159,000.
June	Filter effluent	52.	6.	11.4	3.8	2.	6.	39.2	8.4	10 days.	
July	Raw sewage	134.	35.	61.0	29.2	0	0	68.1	89.	½ day.	
July	Tank effluent	86.	20.	34.2	10.1	0	0	52.	61.	3 days.	2,169,000.
July	Filter effluent	35.	12.	10.2	4.1	0.5	5.	48.	12.	10½ days	
Aug.	Raw sewage	147.	61.	56.2	35.0	0	0	71.2	91.3	½ day.	
Aug.	Tank effluent	76.	16.	20.4	8.0	trace	trace	49.1	54.2	3 days.	1,689,000.
Aug.	Filter effluent	32.	10.	12.1	5.0	1.0	4.2	44.2	11.1	10 days.	
Sept.	Raw sewage	116.	35.	48.2	38.1	0	0	78.2	91.2	½ day.	
Sept.	Tank effluent	84.	20.	18.4	23.	trace	trace	58.1	5 .4	3½ days.	1,540,000.
Sept.	Filter effluent	40.	15.	8.4	5.5	1.5	4.5	49.1	10.5	11 days.	

*Filter beds were not used after November until May, 1908.

TABLE NO. 4.

ANALYSES OF SEWAGE AND EFFLUENTS AT THE MADISON, WIS., MUNICIPAL PLANT FOR THE MONTH OF OCTOBER, 1907.

Quantities are parts per million.

Date.	Sample.	Solids in suspension.		Free NH3	Alb. ammonia.	Nitrites.	Nitrates.	Chlorine.	Oxygen consumed.	Putrescibility test.	Amount of sewage in gal. per day.
		Total.	Fixed.								
1907. Oct. 2	Raw sewage....	138.	40.	26.85	4.	0	0	98.	82.5	½ day.	
Oct. 2	Tank effluent ...	72.	15.	14.25	2.25	trace	0	79.5	28.3	1½ days.	2,004,000
Oct. 2	Filter effluent.,..	40.	13.	11.0	1.25	0	0.5	70.5	8.5	5 days.	
Oct. 8	Raw sewage....	129.	35.	39.25	4.5	0	0	89.6	79.6	½ day.	
Oct. 8	Tank effluent ...	65.	8.	28.25	3.25	trace	0	50.	26.3	1½ days.	3,600,000
Oct. 8	Filter effluent ...	43.	14.	18.5	2.25	1.	0.3	47.5	7.5	3 days.	
Oct. 9	Raw sewage....	130.	37.2	41.	5.24	0	0	94.8	69.5	1 day.	
Oct. 9	Tank effluent ...	78.	18.	28.7	2.5	0	0	56.9	25.1	2 days	2,014,000
Oct. 9	Filter effluent . .	45.	12.	8.	1.5	trace	0.52	52.4	8.3	6 days.	
Oct. 11	Raw sewage....	132.	36.5	42.5	6.5	0	0	97.8	73.4	½ day.	
Oct. 11	Tank effluent ...	62.	16.	24.5	2.5	trace	0	60.5	28.1	2 days.	1,949,000
Oct. 11	Filter effluent ...	51.	11.	5.5	0.5	trace	0.9	54.3	9.0	6 days.	
Oct. 14	Raw sewage....	133.5	32.	41.5	8.75	0	0	89.8	71.5	½ day.	
Oct. 14	Tank effluent ...	85.4	17.5	30.5	3.75	.5	0	48.3	30.2	2 days.	1,634,000
Oct. 14	Filter effluent ...	45.	13.5	19.5	0.75	trace	1.2	41.8	9.5	3 wks.	
Oct. 16	Raw sewage....	139.6	35.4	43.75	8.5	0	0	100.5	68.3	½ day.	1,885,000
Oct. 16	Tank effluent ...	79.	20.	36.25	2.0	0.7	0	62.0	32.8	2 days.	
Oct. 16	Filter effluent ...	50.	10.	13.75	1.25	0.6	1.0	58.1	10.3	10 days.	
Oct. 21	Raw sewage....	145.1	38.	42.5	3.75	0	0	94.8	72.[illegible]	½ day.	
Oct. 21	Tank effluent ...	92.0	21.0	30.25	4.5	0	0	56.2	36.9	2 days.	1,758,000
Oct. 21	Filter effluent ...	52.0	17.0	19.5	1.15	1.	0	52.7	11.2	10 days.	
Oct. 23	Raw sewage....	140.2	30.0	42.	4.0	0	0	81.8	85.2	½ day.	
Oct. 23	Tank effluent ...	82.3	20.1	32.25	3.0	0	0	42.	46.2	2 days.	1,758,000
Oct. 23	Filter effluent....	56.4	16.	20.0	1.0	0.5	0	35.5	12.1	10 days.	
Oct. 28	Raw sewage....	138.5	28.	41.	4.5	0	0	78.5	75.	½ day.	
Oct. 28	Tank effluent....	74.2	18.3	31.5	3.0	0	0	39.	38.	1½ days.	1,885,000
Oct. 28	Filter effluent....	42.3	12.	18.5	0.75	0.5	0	31.5	13.	9.5 days.	

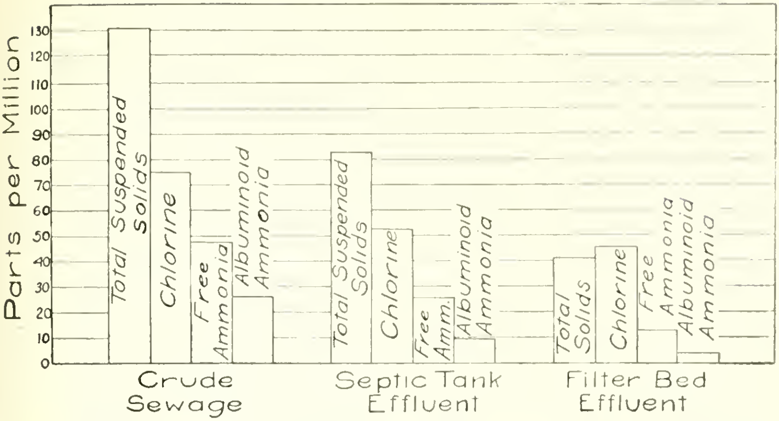


FIGURE 16.—COMPARISON OF SEWAGE AND EFFLUENTS AT MADISON, WIS.

monia. This is an inorganic substance and in every way harmless, but it is not a stable compound, when turned into a stream. The loss of albuminal ammonia is caused by the decomposition of organic compounds. The action is similar to digestion or peptonization or conversion into a soluble form.

In passing through both the tank and the filter beds, there was a reduction of 70 per cent. of the solids in suspension, 38 per cent. of chlorine, 74.5 per cent. of free ammonia and 84 per cent. of albuminoid ammonia, in comparison with the raw sewage.

The loss of solids in suspension in passing through the filters was caused by their being held on or in the filter beds. The loss in chlorine can only be accounted for as changing into chlorates through aeration of the effluent. The albuminoid ammonia was broken up into gases and water. The free ammonia was oxidized into carbon dioxide and water, by the nitrifying bacteria in the filter bed.

In connection with the chemical analysis of the effluents, there was also carried out the putrescibility test by the methylene blue method. In Figure 17, the putrescibility tests of the effluents of the Madison plant have been plotted to scale. The effects of the seasons upon the degree of purification is very well

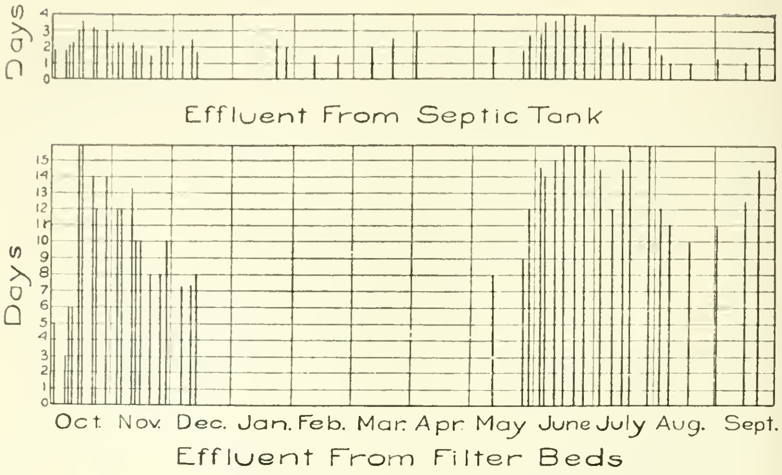


FIGURE 17.—PUTRESCIBILITY TESTS AT MADISON, WIS.

illustrated here. There was a decrease in the stability of the effluents from the tank commencing with the last of November and lasting to May. Then there was a decided increase during the warm weather, until in August, before the tanks were cleaned, and then there was a decrease until the tanks were started again.

The filter beds were not used from January to April. The effluent from the septic tanks, when the beds are not in use, is turned into the Yahara River which flows into Lake Monona. When the filter beds are used, the effluent is much better.

PLANT AT MENDOTA HOSPITAL

Besides studying the municipal plant at Madison, several institutional plants have been investigated. A good example of an institutional plant is the one at Mendota Hospital, Mendota, Wis.

When the study of this plant was begun in October, 1907, the septic tank had not been cleaned for two years or more. The scum was so hard that it had to be cut out with an ax.

In Table No. 5 of analyses of the sewage and effluents of the Mendota plant, can be seen the variation in the degree of puri-

TABLE NO. 5.

ANALYSES OF SEWAGE AND EFFLUENTS AT THE MENDOTA HOSPITAL PLANT, MENDOTA, WISCONSIN.

Quantities are parts per million.

Date.	Sample.	Solids in suspension.		Free ammonia.	Alb. ammonia.	Nitrites.	Nitrates.	Oxygen consumed.	Chlorine.	Putrescibility test.
		Total.	Fixed.							
1907										
Oct. 12..	Raw sewage.....	120.0	26.0	42.5	8.6	0	0	60.0	101.0	7 hours.
Oct. 12..	Tank effluent...	81.0	14.0	29.75	6.5	0	0	40.0	62.0	1½ days.
Oct. 12..	Filter effluent...	38.0	12.0	14.0	3.0	0.6	trace	15.0	49.0	3 days.
Oct. 16..	Raw sewage.....	124.0	21.0	23.0	8.75	0	0	68.0	89.2	7 hours.
Oct. 16..	Tank effluent....	71.0	17.5	25.0	4.25	0	0	48.0	59.4	¾ day..
Oct. 16..	Filter effluent...	51.0	10.0	21.0	2.0	trace	trace	18.0	46.0	4 days.
Oct. 22..	Raw sewage......	129.2	28.1	15.5	4.0	0	0	65.0	91.0	6 hours.
Oct. 22..	Tank effluent....	106.5	25.0	29.5	6.5	0	0	68.1	81.0	1½ days.
Oct. 22..	Filter effluent...	34.0	11.0	12.25	5.0	2.0	3.0	39.0	52.0	4 days.
Oct. 26..	Raw sewage......	120.0	29.0	28.4	8.1	0	0	65.0	95.0	6 hours.
Oct. 26..	Tank effluent...	98.0	27.1	30.3	10.2	0	0	69.9	71.0	1½ days.
Oct. 26..	Filter effluent...	61.0	15.0	18.0	3.5	0.8	1.0	18.0	54.0	3 days.
Oct. 31..	Raw sewage......	128.5	30.0	35.4	9.0	0	0	61.0	88.4	6 hours.
Oct. 31..	Tank effluent....	79.2	16.2	30.2	4.5	0	0	42.0	69.0	1½ days.
Oct. 31..	Filter effluent...	48.5	14.1	16.0	3.8	0.6	0.9	17.0	49.0	2½ days.
Nov. 19..	Raw sewage......	132.0	32.0	18.4	10.6	0	0	72.0	88.0	8 hours.
Nov. 19..	Tank effluent....	61.0	19.0	14.6	9.0	0	0	41.0	54.0	1½ days.
Nov. 19..	Filter effluent...	35.0	12.0	10.0	3.0	2.0	2.8	20.0	42.0	6 days.
Nov. 23..	Raw sewage......	140.0	31.0	20.1	6.0	0	0	61.0	82.0	6 hours.
Nov. 23..	Tank effluent....	60.0	17.5	12.1	11.7	0	0	32.0	65.0	2 days.
Nov. 23..	Filter effluent...	32.0	12.0	9.0	8.0	1.5	2.0	12.0	39.0	5¼ days.
Nov. 26..	Raw sewage......	125.0	27.1	32.0	9.25	0	0	58.0	65.0	7½ hours.
Nov. 26..	Tank effluent....	71.0	18.1	25.0	2.5	0	0	36.0	38.5	2½ days.
Nov. 26..	Filter effluent...	38.0	10.0	10.1	2.0	2.5	3.0	10.0	30.2	6 days.
Dec. 1..	Raw sewage......	129.5	28.1	39.0	11.0	0	0	61.0	69.0	6 hours.
Dec. 1..	Tank effluent....	76.2	19.0	30.0	3.0	0	0	43.0	45.0	2½ days.
Dec. 1..	Filter effluent...	34.8	11.5	9.4	1.8	1.9	3.1	11.0	32.0	6¼ days.
Dec. 5..	Raw sewage......	132.0	30.0	35.0	9.2	0	0	68.	86.0	8 hours.
Dec. 5..	Tank effluent....	65.0	18.2	26.0	5.4	0	0	32.0	64.4	2½ days.
Dec. 5..	Filter effluent...	38.4	12.1	18.	3.2	1.5	3.0	17.0	49.24	5½ days.
Dec. 12..	Raw sewage......	125.0	32.0	32.4	10.6	0		71.0	71.0	7 hours.
Dec. 12..	Tank effluent....	71.3	19.2	21.5	4.2	0	0	45.0	56.0	3 days.
Dec. 12..	Filter effluent...	56.0	12.0	14.3	3.1	0.9	2.0	19.5	47.5	4 days.
Dec. 19..	Raw sewage......	126.0	28.0	32.0	9.25	0	0	72.0	88.0	7 hours
Dec. 19..	Tank effluent....	54.0	16.5	25.0	3.6	0	0	29.0	61.0	2 days.
Dec. 19..	Filter effluent...	25.0	10.0	10.0	2.5	1.8	3.2	14.0	54.0	5 days.
1908										
Apr. 2..	Raw sewage......	119.0	27.0	42.6	9.2	0	0	60.0	88.2	7½ hours.
Apr. 2..	Tank effluent ...	82.0	15.0	29.75	5.8	0	0	42.0	65.0	3¼ days.
Apr. 2..	Filter effluent...	31.0	13.5	12.0	3.5	1.2	1.8	12.8	54.0	5¼ days
May 7..	Raw sewage.....	126.0	29.5	31.2	12.0	0	0	58.0	76.0	6 hours.
May 7..	Tank effluent....	76.0	16.4	42.0	10.1	0	0	39.0	58.0	3¼ days
May 7..	Filter effluent...	35.0	12.0	15.0	4.6	1.5	0.8	13.0	46.5	6 days.
July 6..	Raw sewage......	142.0	32.1	39.2	10.1	0	0	55.0	71.0	6 hours.
July 6..	Tank effluent....	84.0	21.0	36.3	6.1	0	0	36.0	56.0	3 days.
July 6	Filter effluent...	42.0	14.5	12.5	3.6	1.2	0.9	14.0	44.0	4½ days.
Aug. 22..	Raw sewage......	126.0	25.0	40.1	10.2	0	0	50.0	76.0	6½ hours.
Aug. 22..	Tank effluent....	71.0	18.0	36.2	6 2	0	0	32.0	52.4	4 days.
Aug. 22..	Filter effluent...	32.0	12.5	14.0	4.0	1.3	1.0	10.0	38.1	10 days.
1909										
Jan. 25..	Raw sewage..	132.0	22.5	25.0	8.5	0	0	63.2	108.0	5 hours.
Jan. 25..	Tank effluent....	61.0	14.24	16.0	4.5	trace	trace	54.2	86.0	4 days.
Jan. 25..	Filter effluent...	20.0	9.5	6.0	2.5	1.5	2.0	7 6	69.0	14 days.

fication caused by the cold weather and by the cleaning of the tanks. One tank was cleaned in November, 1907, and the other in August, 1908. In cold weather the purifying action is not nearly so rapid, consequently the degree of purification is not as high as it is in warm weather. In the fall, just before the tank was cleaned, the degree of purification was very low. This is very well illustrated in Figure 18 in the putrescibility tests. In the Mendota Hospital plant, the purification of the sewage was effected by means of septic tanks and filter beds, as described on page 27.

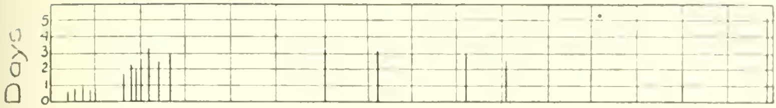
PLANT AT NATIONAL SOLDIERS' HOME

The plant at the National Soldiers' Home, Milwaukee, Wisconsin, is of interest on account of the use of filter beds alone. In Table 6, can be seen the analyses of the raw sewage and the effluent from the filter beds of this plant. The effluent shows up very well. Generally a reduction of 60 to 75 per cent. of organic matter is obtained, which is pretty good since no preparatory treatment is used. In every case of samples from this plant that were examined, the effluent was a non-putrescible one. It has very little odor, more of an earthy one, and very little sediment matter.

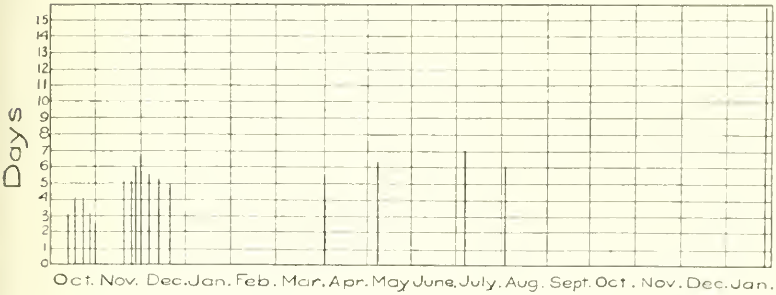
PLANT AT THE ALLIS-CHALMERS SHOPS

The disposal plant at the Allis-Chalmers Shops, at West Allis, Wisconsin, is interesting as the effluent is used again in the shops for sanitary purposes, boilers, and for washing after being purified. Such use has an advantage in that the purified sewage is not nearly so hard as the city water is, and therefore they are not bothered much with boiler scale. The plant is described on page 30.

The examination shows that there is a purification of 75 to 80 per cent. in the septic tank and 5 to 10 per cent. further purification in the anaerobic filter. The most that the anaerobic filter seems to do is to remove part of the solids, both those in suspension and those in solution in the sewage. In the effluent from the trickling filter, there is secured a great improvement. The degree of purification effected by the entire plant does not vary a great deal, but runs as high as 94 per cent. sometimes.



Effluent From Septic Tank.



Effluent From Filter Bed

FIGURE 18.—PUTRESCIBILITY TESTS AT MENDOTA, WIS.

TABLE NO. 6.

ANALYSES OF SEWAGE AND EFFLUENTS AT THE NATIONAL SOLDIERS' HOME PLANT, MILWAUKEE, WISCONSIN.

Quantities are parts per million.

Date.	Sample.	Solids in suspension.		Free ammonia.	Alb. ammonia	Nitrites.	Nitrates.	Oxygen consumed.	Chlorine.	Putrescibility test.
		Total.	Fixed.							
1908.										
Aug. 25.	Raw sewage.....	129.	31.	39.5	54.0	0	0	65.	92.5	9 hours.
Aug. 25.	Filter effluent...	71.2	18.	1.5	11.5	0	0	49.8	69 2	4 days.
Sept. 10.	Raw sewage.....	130.5	28.	40.2	48.2	0	0	72.0	85.4	8 hours.
Sept. 10.	Filter effluent...	49.2	15.	3.5	12.2	trace	trace	45.0	55.2	4 days.
Sept. 17.	Raw sewage.....	125.	27.	36.4	48.3	0	0	60.8	82.5	7 hours.
Sept. 17.	Filter effluent...	39.5	14.	8.1	10.1	0.2	0.5	40.5	61.	3½ days.
Oct. 1.	Raw sewage.....	128.	26.	60.5	32.	0	0	68.	71.6	6 hours.
Oct. 1.	Filter effluent...	25.1	12.	15.	10.	0.5	0.8	42.	54.	4 days.
Oct. 14.	Raw sewage.....	125.	28.6	45.5	35.0	0	0	72.5	76.	7 hours.
Oct. 14.	Filter effluent...	35.0	17.2	12.	10.5	0.5	0.7	35.	48.	4½ days.
Nov. 7.	Raw sewage.....	140.	25.4	38.1	28.1	0	0	61.	69.	8 hours.
Nov. 7.	Filter effluent...	32.3	10 4	8.	7.4	0.6	1.0	28.	38.	5 days.
Nov. 25.	Raw sewage.....	135.	29.0	40.	35.0	0	0	68.	71.	8 hours.
Nov. 25.	Filter effluent...	28.	9.0	6.	8.2	1.0	1.5	27.7	32.2	5 days.
Average	Raw sewage.....	130.5	26.42	43.	40.08	......	......	66.7	78.2	8 hours
Average	Filter effluent...	40.	13.62	7.7	9.9	......	......	38.8	51.0	4½ days.

The trickling filter represents the latest method of sewage purification. In Table No. 7 will be found some analyses of the sewage and the various effluents. During the period over which the investigations extended, this plant has been handling only one-third to one-half of the quantity of sewage for which it was designed, owing to the shops being operated with a small force on account of the prevailing business depression.

The sewage at this plant consists, for the most part, of closet wastes, wash water from toilet rooms and some grease and oil. The grease and oil is skimmed off and does not run into the septic tank. The sewage is weaker than an ordinary city sewage.

TABLE NO. 7.

ANALYSES OF SEWAGE AND EFFLUENTS AT THE ALLIS-CHALMERS PLANT MILWAUKEE, WISCONSIN.

Quantities are in parts per million.

1908. Date.	Sample.	Solids in suspension.		Free ammonia.	Alb. ammonia.	Nitrites.	Nitrates.	Oxygen consumed.	Chlorine.	Putrescibility test.	Oxygen dissolved.
		Total.	Fixed.								
June 18.	Raw sewage.....	150.	20.	25.	22.5	0	0	48.4	100.	5 hours	3.2
June 18.	Tank effluent ...	28	12.	33.	16.0	0	0	45.0	28.	3½ days	4.0
June 18.	Anaerobic filter effluent	18.	6.	7.2	1.2	1.0	0.5	40.	25.	5 days	9.0
June 18.	Trickling filter effluent	12.	4.	8.8	0.4	1.5	1.0	21.	25.	10 days	12.8
Aug. 7.	Raw sewage	142.	22.1	25.0	21.0	0	0	46.6	110.0	10 hours	3.2
Aug. 7.	Tank effluent ...	25.6	12.0	36.5	18.	trace	trace	44.	30.	8 days	5.0
Aug. 7.	Anaerobic filter effluent	16.5	7.0	9.6	1.7	1.5	1.0	38.9	28.0	10 days	10.0
Aug. 7	Trickling filter effluent	11.5	3.0	9.4	0.7	2.0	3.0	22.	24.0	12 days	14.8
Oct. 10	Raw sewage.....	144.0	25.0	26.3	23.5	0	0	50.2	105.	11 hours	3.6
Oct. 10	Tank effluent ...	28.5	11.6	31.0	15.0	0	0	46.0	30.	5 days	6.0
Oct. 10	Anaerobic filter effluent	17.8	5.0	8.1	1.3	1.2	1.6	39.	25.	8 days	11.0
Oct. 10	Trickling filter effluent	10.2	3.5	7.0	0.5	1.9	2.5	18.	22.	10 days	15.2
Nov. 20	Raw sewage. .	145.	25.	28.5	23.8	0	0	70.8	109.	8 hours	4.0
Nov. 20	Tank effluent ...	29.2	10.	33.2	15.0	0	0	61.	35.	4 days	5.1
Nov. 20	Anaerobic filter effluent	16.9	6.	7.1	1.8	0.9	0.8	48.	26.	8 days	9.6
Nov. 20	Trickling filter effluent	11.1	4.	5.2	0.6	2.	3.2	16.	21.	12 days	16.0
1909.											
Jan. 28.	Raw sewage.....	150.2	20.0	29.8	25.0	0	0	67.	112.0	9 hours	3.8
Jan. 28.	Tank effluent ...	30.5	10.1	34.6	14.8	trace	0	58.	30.0	4 days	4.8
Jan. 28.	Anaerobic filter effluent	15.	5.	8.1	1.5	1.0	1.2	40.	22.5	9 days	9.1
Jan. 28.	Trickling filter effluent	8.	3.	5.5	0.5	1.5	3.0	20.	20.0	14 days	14.9

METHODS OF SAMPLING AND ANALYSIS

The samples were analyzed as soon as they were received at the laboratory. Samples were collected at the same time each day.

Chloroform was used as the preservative. The standard methods of analysis were followed throughout with the exception of the oxygen-consumed test, which was made with the cold process with ten minutes boiling. For the putrescibility test, the sewage was incubated at 37° C. for four days.

The work on the Wisconsin plants, just discussed, shows that they are capable of rendering a satisfactory degree of purification of the sewage reaching them, except during the cold season, provided a reasonable amount of intelligent care is given to them. No data are available as to what quality of effluent the filters would produce during the winter, owing to the custom, prevalent at practically all of these plants, of closing down the filters in the winter.

In order to make a comparison of the merits of the various devices and types of plants in use in the state, it is necessary that they should be operated under practically similar conditions and that they be given equal amounts of care. To make such a comparison possible, the discussion of methods of operation, given in this bulletin, has been prepared in the hope that it would promote more thorough and uniform care of the plants, and that in some instances an attempt would be made to operate the plants through the winter by some of the methods suggested. If such a result is attained, this investigation could profitably be renewed and carried on more thoroughly and on a larger scale.

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TESTS ON BOND BETWEEN CONCRETE AND STEEL IN REINFORCED CONCRETE BEAMS

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MADISON, WISCONSIN
OCTOBER, 1909

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TESTS ON BOND BETWEEN CONCRETE AND STEEL IN REINFORCED CONCRETE BEAMS

I. INTRODUCTION

Since an adequate bond between concrete and embedded steel has long been a recognized necessity in reinforced concrete construction, many experiments have been made to establish safe working values. Such tests on bond have generally been made by embedding a rod in a block of concrete and pulling it out in a testing machine. In most tests this has been done in such a way that the concrete surrounding the rod has been compressed. While the results of such tests made by one experimenter frequently agree fairly well among themselves, there is a wide variation among the results as a whole. This variation, and the belief that other conditions than those ordinarily encountered in beams or slabs influenced the results obtained from the cylinder tests, were the incentives for making the tests on bond in beams recorded in this bulletin.

Furthermore, in view of the claim advanced by some advocates of deformed bars that repeated loading would destroy the bond between concrete and steel, it was decided to make some tests of this nature on beams containing plain and deformed bars.

In what follows the word "static" is frequently used in connection with beams progressively tested to failure under loads gradually applied, and the word "repeated" occurs in connection with those beams subjected to repeated loadings.

The tests may be divided into two parts,—static tests, in which plain round rods were used, and repeated tests, in which plain round, rusted round and corrugated bars were employed.

The larger portion of the static tests was made as a thesis by

A. B. Carey, S. L. Clark and P. B. Johnson of the class of 1907, to whom due acknowledgment is hereby made. The repeated tests were very efficiently conducted by J. O. Reed and S. J. Williams of the class of 1908. To their careful work and thought the success of these tests is due. They are also deserving of credit for an exceptionally well written report, recording their results and conclusions. The air cylinder and rotating valve were designed by H. F. Moore, formerly assistant professor of mechanics at this university. Acknowledgment is also made to the Expanded Metal and Corrugated Bar Co. of St. Louis for the corrugated bars donated.

II. MATERIALS

Cement. Atlas Portland cement from Missouri was used in all tests. Table I is a record of strength tests made on the cement used in the static bond tests. The time of initial set was 45 minutes, and the time of final set 5 hours and 40 minutes. The cement also passed the standard soundness test.

Sand. The sand employed in these tests was a rather fine local bank sand and contained about 3 per cent. of fine dirt. Table II contains the results of the mechanical analysis made.

TABLE I.

TENSILE STRENGTH OF ATLAS CEMENT USED IN STATIC BOND TESTS.

BRIQUETT NUMBER.	ULTIMATE STRENGTH LBS/IN^2			
	Age 7 days.		Age 28 days.	
	Neat.	1:3 Mortar.	Neat.	1:3 Mortar.
1	510	155	460	300
2	500	190	735	345
3	545	245	540	240
4	560	225	900	350
Average	529	204	659	309

TABLE II.

ANALYSIS OF SAND.

Per cent voids=37.5.
Weight per cu. ft.—103 lbs.

Sieve No.	Diameter of mesh. Inches.	Per cent passing.
6	.131	100
10	.073	97.4
16	.042	91
20	.034	88
30	.022	75.4
40	.015	58.4
50	.011	31.6
74	.0078	15.5
100	.0045	8.8

Stone. Crushed limestone from Kankakee, Illinois, was used in the static bond tests. Its mechanical analysis is given in Table III. A local bank gravel was obtained for beams 19 and 20 of this series, all particles less than 0.2 inches in diameter being screened out. It weighed 105 pounds per cubic foot and contained 35½ per cent. voids.

In the repeated bond tests, the stone was a crushed limestone obtained from a local quarry. The mechanical analysis of this stone will be found in Table III A.

Steel. The plain round rods used in all tests were purchased from a local firm. Except as noted below, all bars were free from loose scales and rust. Care was taken to remove all lips at the ends of the bars, due to the rod cutter, which might affect

TABLE III.

Analysis of Kankakee Limestone Used in Static Bond Tests.

Per cent voids=48.5
Weight per cu. ft.=83 lbs.

Diameter of Mesh ins.	Amount retained bs.	Per cent. passing.
1	0	100
¾	2.00	95
½	27.25	26.4
.2	9.00	3.8
.034	1.06	1.1
Dust	0.44	

TABLE IIIa.

Analysis of Local Limestone Used in Repeated Bond Tests

Per cent voids = 19.3.
Weight per cu. ft. = 83 lbs.

Diameter of Mesh ins.	Amount retained lbs.	Per cent passing
1¼	1.0	97.6
1	2.5	91.6
¾	20.75	42.2
⅜	12.25	13.0
¼	5.5	0.0

the bond. Nine months' exposure to the weather had created a firm coating of hard rust on the rusted plain round rods. Before these were placed in the beams, they were tapped sharply with a hammer to remove any loose scales. The "new style" corrugated bars were donated by the Expanded Metal and Corrugated Bar Company of St. Louis. Table IV contains results of tensile tests made on the steel used. Values above the black line are for specimens from rods used in the static bond tests while values below the line are for those used in the repeated bond tests. The latter values were obtained from specimens cut from the ends of the rods used in the beam tests.

TABLE IV.

Tension Tests of Steel.

Size of bar inches.	Kind.	Stress at yield point lbs/ins ^{2}	Ultimate strength lbs/ins ^{2}	Modulus of elasticity lbs/ins ^{2}	Percentage elongation in 8 inches.
⅜............	Plain round.	46,000	62,600	31,600,000	26.1
½.......... .	Plain round.	44,000	64,900	30,700,000	28.1
⅝............	Plain round.	46,000	68,100	30,600,000	....
¾............	Plain round.	42,000	64,000	29,300,000	28.1
1............	Plain round.	44,000	61,000	29,400,000	25.4
1............	Plain round.	41,300	60,100	*28,600,000	29.8
⅝............	Plain round.	40,000	....	30,000,000	....
⅝.	Plain round.	39,000	59,300	30,000,000	19.5
Average	Plain round.	39,500	59,300	30,000,000	19.5
½............	Corrugated ..	43,000	76,800	29,600,000	10.1
½............	Corrugated ..	42,000	75,840	28,200,000	12.5
½............	Corrugated ..	42,500	78,800	27,400,000	16.4
Average	Corrugated ..	42,500	77,150	28,400,000	13.0
½............	Rusted.......	33,500	54,100	28,000,000	13.2
½......	Plain round.	34,000	49,700	28,000,000	9.4
Average	Plain round.	33,750	51,900	28,000,000	11.3

*Average of tests on three bars used in beams 65, 66 and 67.

Concrete. In making concrete, materials were proportioned by volumes, measured loose, one hundred pounds per cubic foot being assumed as the specific weight of cement. Quantities required were weighed. Concrete for beams 1 to 49 was mixed by hand on the cement floor in the laboratory. The cement and sand were mixed dry until the mass was uniform in color. This mixture was shovelled upon the wetted stone and turned four times. Water was then added and the whole mass turned until the desired consistency obtained throughout the batch.

All other beams were mixed in a No. 0 Smith batch mixer. The time allotted to mixing a batch by machine was about three minutes. Three consistencies were used in beams 23 to 31, wet, medium, and dry. The wet concrete was sloppy, could not be piled up on the mixing floor, and when placed in the molds showed an excess of water on top. The medium concrete, when piled on the floor, would flatten out, could be readily worked around the reinforcement without much tamping and easily surfaced with a trowel. The dry concrete was very mealy, would stand piled up on the floor, required hard tamping and could not be readily surfaced with a trowel. The medium consistency was used in all other beams subjected to static loads. The beams tested under repeated loads were made of a consistency slightly drier than the medium mentioned above.

III. SPECIMENS

MAKING—CURING—APPARATUS

Beams. Fifty-four beams were made for the static bond tests. Those made from the same batch of concrete are arranged in groups in Table V. For the repeated bond tests, thirty-one beams were made. In Tables XIV, XV, XVI, and XVII, referring to these tests, the letter before the number indicates the batch from which the beam was made.

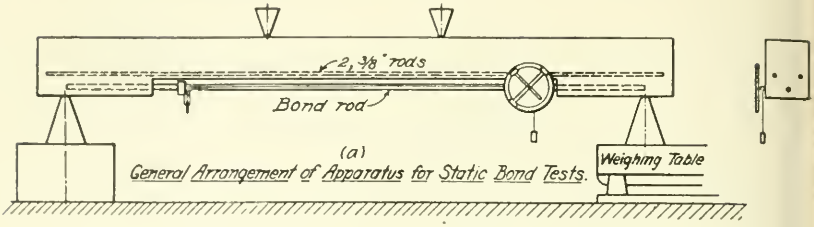
The general arrangement of reinforcement in these beams is shown in Figure 1. As may be seen in the figure, they were so made that the central portion of the lower rod, whose bond was to be obtained, was exposed. Two ⅜-inch round rods were placed above the lower rod, as shown in the figure, to distribute the tension cracks and prevent failure in the concrete before the lower rod slipped.

TABLE V.

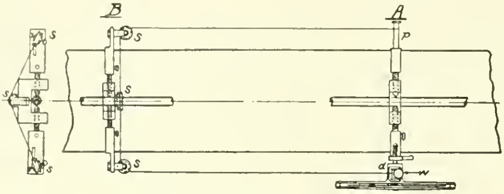
Data on Specimens Made for Static Bond Tests.

Beam No.	Mix.	Consistency.	Size of rod ins.	Age.	Variable studied.	Kind of auxiliary specimens.
1- 2	1:2:4	Medium.	⅝	7 da.	Time.	Compression.
4- 5- 6	"	"	⅝	28 "	"	"
7- 8- 9	"	"	⅝	60 "	"	"
10-11-12	"	"	⅝	6 mos.	"	"
7- 8- 9	"	"	⅝	60 da.	Mix.	"
17-18	1:3:6	"	⅝	"	"	"
*19-20	1:2:4	"	⅝	"	"	"
21-22	1:2½	"	⅝	"	"	"
23-24-25	1:2:4	Wet.	⅝	"	Consistency.	....
26-27-28	"	Medium.	⅝	"	"	....
29-30-31	"	Dry.	⅝	"	"	....
36-37	"	Medium.	⅝	"	Method of test	Bond.
38-39-40	"	"	⅝	"	Size of rods	"
41-42-43	"	"	½	"	"	"
44-45-46	"	"	¾	"	"	"
47-48-49	"	"	1	"	"	"
54-55-56-57	"	"	⅝	28 da.	Time and loading.	Compression.
58-59-60-61	"	"	⅝	"	Loading.	"
62-63-64	"	"	⅝	29 da.	Loading.	Bond and Compression.
65-66-67	"	"	1	58 da.	Size of rods and loading.	Bond and Compression.

* In 19 and 20 gravel was used in place of limestone.



(a)
General Arrangement of Apparatus for Static Bond Tests.



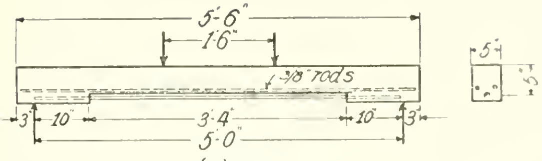
(b)
Extensometer Used

FIGURE 1.—METHOD OF REINFORCING BEAMS AND EXTENSOMETER USED.

Table V contains data on the beams made for the static tests. The dimensions, position of reinforcement, etc., are shown in Figure 2. The beams made for the repeated bond tests were all 5 feet 6 inches long, 6 inches wide, and 6 inches deep. The length of embedment of the lower bar was, in all cases, practically 10 inches at either end. Figure 2a shows arrangement of reinforcement and dimensions of these beams.

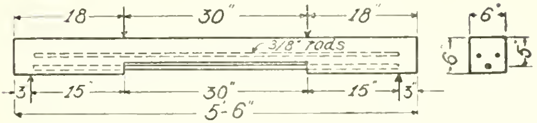
Auxiliary Specimens. Compression specimens were fabricated from nearly every batch of concrete. With the beams for static bond tests, either 4-inch cubes or cylinders 6 inches in diameter and 18 inches long were made. Cylinders 10 inches in diameter and 24 inches long were cast with bond beams used for the repeated tests.

Bond cylinders 6 inches in diameter and 18 inches long were also made from many of the batches of concrete. In each of these a rod was embedded with its axis coinciding with that of the cylinder. The length of embedment was 12 inches in those made with the beams for the static tests, except for the cylinders made with beams 65, 66, and 67, where the length of embedment was 18 inches. In all bond cylinders made with beams for the repeated tests, the length of embedment was 10 inches. Figure 3a shows type of bond cylinder used.



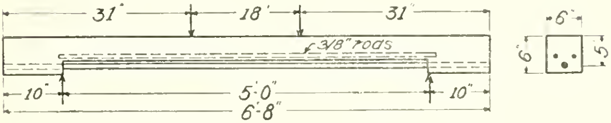
(a)

Beams 1-57



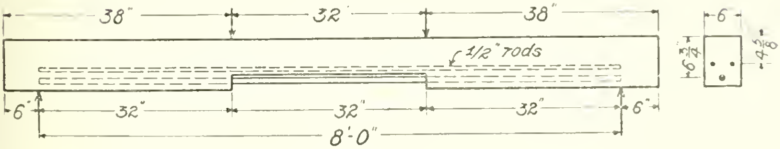
(b)

Beams 62 64



(c)

Beams 58-61



(d)

Beams 65-67

FIGURE 2.—DIMENSIONS, POSITION OF REINFORCEMENT AND METHOD OF LOADING BEAMS.

Making. Wooden forms were used in making beams 1 to 49; forms composed of steel channels in making all others. Two notched pieces of wood, placed transversely with respect to the axis of the beam and on the bottom of the form, served to space the lower rod and provide a definite limit for the predetermined length of embedment. Exposure of the lower rod was secured by filling in between the wooden pieces with a layer of damp sand of sufficient depth to cover the rod about ½ inch. This was thoroughly compacted and smoothed off with a trowel before the beam was cast. Figure 4 shows a mold ready for concrete.

Concrete was first carefully placed around the exposed portions of the lower rod. Then a thin layer was spread over the whole length of the beam and the two upper rods put in place. The form was then filled, the concrete worked with a trowel and the top finished. In making the beams of dry consistency, concrete was tamped with an iron tamping bar.

All auxiliary specimens were made in cast iron or steel molds which were set upon leveled steel plates. Concrete was deposited in layers 4 to 6 inches deep and puddled with a steel rod.

Curing. Beams, and corresponding auxiliary specimens, 1 to 49 were kept in the molds from three to ten days after mixing and were then allowed to cure in the air of the laboratory without being sprinkled. All other beams were kept in the molds from two to four days, generally three days, and were then sprinkled every day for at least one week, after which they were stored in the laboratory until tested. The temperature of the room in which the beams were kept varied approximately from 60° to 80° F.

Apparatus. All beams were tested in a 100,000-pound Olsen hydraulic transverse testing machine. The general scheme of loading used in the static tests is shown in Plate 1. The positions of the loads and reactions for the different beams tested are given in Figure 2. Steel bearing plates were placed on the supports and under the loads to prevent crushing of the concrete.

In making the repeated bond tests, 2 inch steel rollers were used instead of knife edges, both at supports and at loading points, and the bearing plates were set in plaster of paris. Loads

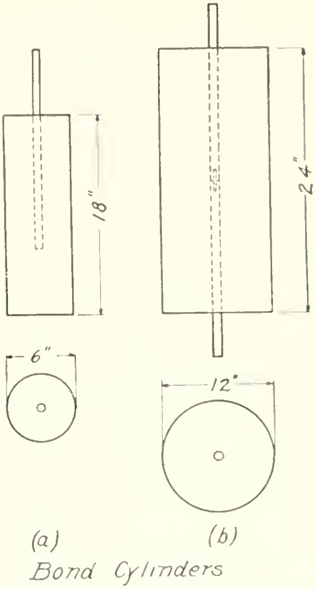


Figure 3.—Types of Bond Cylinders.

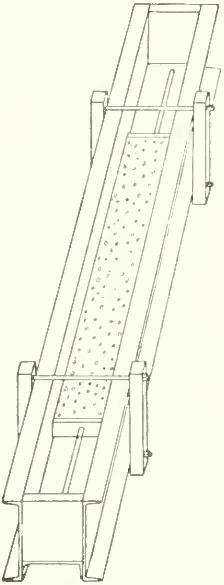


Figure 4.—Mold for Beams.

were transmitted from the cross-head of the machine to the test specimen through a 6-inch rail weighing 70 pounds per yard.

A dial extensometer was used in all tests to measure elongation of the lower rod. This extensometer, attached to a rod, is shown in Figure 1b. The relative motion of part A of the extensometer with respect to part B was transmitted through a No. 36 covered copper wire attached to the pin *p* and carried around the idler pulleys *s, s, s,* to the drum of the dial *d*. The small weight *w* hung on the end of the wire served to keep it taut. The dial read to .0001 of an inch. As can be seen from the figure, the dial recorded twice the average elongation of the specimen in the given gage length. The gage lengths used in testing the beams for static tests are given in Table VI. In the beams for repeated tests, a 30-inch gage length was employed.

The apparatus used in making the repeated tests is shown in Plates I and II. Repeated loadings on a beam were obtained by alternately raising and lowering the right support in Plate I, while the cross-head of the machine was held fixed in position.

To accomplish this, a steel cylinder fitted with an 8-inch ground steel plunger, which could be operated by compressed air, was rigidly bolted to the I-beams of the testing machine as shown. Air was furnished by a compressor equipped with a large storage tank located in the adjoining steam laboratory. The air supply was led to the apparatus through 75 feet of ¾-inch pipe. The intensity of pressure in the pipe line was indicated by means of a gage shown at the extreme right, Plate I. A receiver of about ⅓ cubic feet capacity was installed close to the cylinder to maintain a constant pressure at the rotating valve which served to alternately admit and release air to and from the cylinder. This valve was rotated by means of a ¼ h. p. alternating current motor belted to it, shown at the left in both plates. A globe valve, placed between the gage and receiver, controlled admission of air to the apparatus. An ordinary steam indicator, with its drum held stationary, showed the intensity of pressure in the cylinder. Helmet oil proved to be an excellent lubricant for the plunger. It was not easily blown out by the air pressure, and was an aid in keeping the dust out of the cylinder. A piece of blotting paper, placed over the top of the piston,

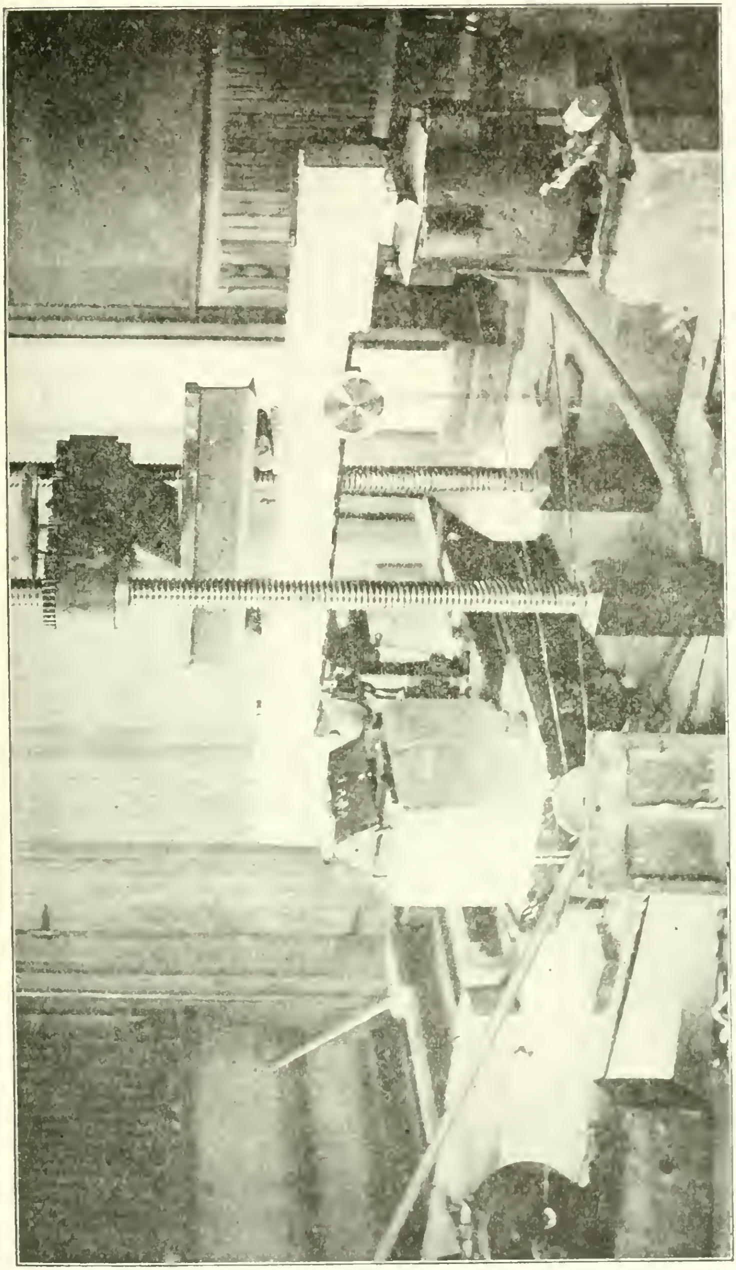


PLATE I. BEAM AND APPARATUS FOR REPEATING LOADS.

prevented particles of grit and dirt from getting in between the cylinder and plunger.

In general, the apparatus worked in a satisfactory manner, although some trouble was caused by the sticking of the rotating valve, due to a defect in construction which could be easily remedied for future tests. Calibrations of the apparatus were made as indicated below. Several determinations of the friction between plunger and cylinder were made by noting scale beam readings on the weighing head and the corresponding indicator reading as the loads on the beam increased. It was found that about 5½ lbs/in^2 of air were required at all pressures to overcome friction, weight of beam, and apparatus upon it. About 2 lbs/in^2 of this amount were necessary to overcome friction alone.

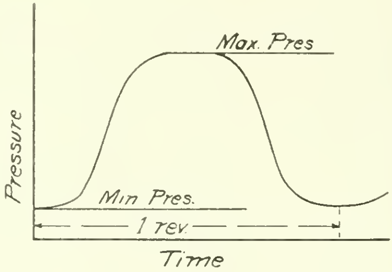


Figure 5.—Curve Showing Shape of Air Pressure—Time Curve.

As the openings in the rotating valve were too small to completely release the air from the cylinder, the minimum pressure was always above that of the atmosphere. In general this minimum pressure was about one-fourth the maximum. Figure 5 shows the shape of the pressure-time curve. This was obtained by rotating the drum of the indicator at constant speed while the valve was running at 100 r. p. m. As will be seen from the shape of this curve, the load was very suddenly applied and remained practically constant in amount for about ¼ of a revolution or .15 of a second. It was also found that the deflection of the end of the beam resting on the plunger was practically the same for the same air pressure applied statically or repeated 100 times per minute. This shows that the stress in the bond rod under repeated loadings was practically the same as it would have been if an equal pressure, at that instant, had been statically applied. This is of importance as the amount of stress in the bond rod when the beam was repeatedly loaded was determined from the air pressure-elongation curve of a static loading.

All small compression specimens were broken in a 100,000-pound Riehlé universal testing machine. The 10-inch cylinders were crushed in the 600,000-pound hydraulic machine.

All bond cylinders, except specimens 6, 7, and 8 in Table XII, were tested in a 50,000-pound Olsen universal machine. The latter three cylinders were tested in the 100,000-pound Riehlé.

IV. STATIC BOND TESTS

The data on specimens made for the static bond tests are given in Table V. The following subjects were studied:

1. effect of age on bond;
2. bond of different mixes;
3. effect of consistency on bond;
4. effect of size of rod on bond;
5. effect of various methods of loading on bond in beams;
6. effect of various methods of testing on bond in cylinders;
7. comparison between cylinder and beam tests on bond.

Method of testing and computation. Beams were tested by applying loads, as shown in Figure 2, in increments of 400 or 500 pounds, and noting the corresponding dial readings. As the load was applied tension cracks appeared on the lower sides of the beams but were prevented from spreading and causing failure by the auxiliary rods placed above the main bar as shown in the figures. All failures were due to slipping of the lower bar. In beam 65 diagonal cracks appeared between the points of loading and the supports but did not develop sufficiently to cause failure. Slipping of the rod was immediately indicated by a backward movement of the pointer on the dial and by the dropping of small particles of sand and concrete from the surface of the rod at the end which slipped. After the beam had failed it was taken out and the concrete removed from the rod at the end which had pulled out so that the condition of the surface of the rod and the actual length of embedment could be observed. In general the rods had full surface contact with the concrete over the predetermined length of embedment. Whenever flaws were detected allowance was made in the values given for the length of embedment in Table VI.

Curves were drawn between loads as ordinates and dial readings as abscissae. From the shape of these curves an estimate of the elongation in the rod due to the weight of the beam and any initial load was made and values of these zero connections

TABLE VI.

RESULTS OF TESTS ON BOND BETWEEN CONCRETE AND STEEL IN BEAMS STATICALLY LOADED.

Beam No.	Gage length of extensometer ins.	Length of imbedment ins.	Load at Max. dial reading lbs.	Zero correction to dial readings ins.	Maximum increment in dial reading ins.	Stress in steel lbs in^2	Bond lbs/in^2
1	2	3	4	5	6	7	8
1	36	10	4,000	.0040	.0287	14,200	222
2	..	10	3,400	.0045	.0267	13,500	211
4	..	11¾	6,800	.0057	.0472	23,000	305
5	..	9⅝	4,400	.0068	.0375	19,200	312
6	..	9¾	4,600	.0055	.0234	12,900	207
7	..	8	4.800	.0050	.0378	18,500	362
8	..	10	4,200	.0069	.0321	16,900	264
9	..	8⅝	4.000	.0055	.0202	11,100	201
10	..	10	4.200	.0070	.0344	17,900	280
11	..	9½	5,200	.0060	.0431	21,300	350
12	..	9¾	4,800	.0066	.0392	19,800	318
17	..	10	3.200	.0073	.0194	11.600	181
18	33	11¼	4.400	.0081	.0301	18,100	251
19	34	11	5.200	.0057	.0376	19,900	282
20	34	10	4.800	.0055	.0320	17.200	269
21	34	11	3,600	.0080	.0281	16,600	235
22	34	9½	3.800	.0080	.0317	18,200	300
23	33¾	$9\frac{9}{16}$	3.200	.0052	.0186	11,000	180
24	34	10	4.800	.0090	.0392	22,100	346
25	34	11½	4.000	.0067	.0293	16,500	224
26	33⅞	10¾	3.200	.0053	.0203	11,800	171
27	34	9	3.600	.0069	.0335	18,500	321
28	33⅞	10	3.500	.0061	.0234	13.600	212
29	34	10½	4,800	.0066	.0355	19,300	287
30	34	10	3,600	.0074	.0364	20,100	314
31	34	9½	3,600	.0067	.0230	13,600	224
36	30	12½	5,400	.0055	.0335	20,300	254
37	30	12½	5.400	.0065	.0363	22.200	278
38	36	7½	3,200	.0132	.0504	27.600	345
39	..	7½	3.400	.0090	.0460	23.800	298
40	..	8¼	2.400	.0078	.0308	16.700	190
41	..	9⅛	4,400	.0120	.0489	26,400	361
42	..	8½	3.600	.0098	.0392	21,200	312
43	..	8¼	2,800	.0052	.0231	12.300	186
44	..	11¼	5.000	.0040	.0247	12.400	207
45	..	$9\frac{1}{16}$	4,400	.0035	.0285	13.900	289
46	..	10	6.200	.0056	.0307	15.700	295
47	..	10¼	3,400	.0017	.0118	5,850	136
48	..	11	4,000	.0031	.0146	7,650	174
49	..	11	4.000	.0020	.0163	7.900	180
54	36¾	$9\frac{15}{16}$	4.500	.0021	.0320	14.500	228
55	36½	10	4.500	.0050	.0322	15,900	248
56	18	9⅞	4.300	.0018	.0144	14.100	222
57	36	10¼	5,000	.0005	.0371	16.300	247
58	26⅜	10⅝	3,400	.0000	.0150	8,800	129
59	25⅜	10½	3,300	.0003	.0152	9.500	141
60	27½	10½	4,100	.0000	.0221	12.600	187
61	26½	10⅜	3,900	.0000	.0232	13.700	204
62	22⅜	15	6,850	.0006	.0270	19.000	197
63	$21\frac{15}{16}$	14¾	6.800	.0000	.0284	20,300	215
64	20¾	14½	7.000	.0003	.0290	22.100	236
65	29¾	32	9,800	.0013	.0497	25,500	199
66	29⅜	32	9.900	.0012	.0498	25,800	202
67	29⅝	32	10.200	.0007	.0463	23,600	184

to the elongations are given in Table VI. The shape of these curves was similar to that of the load-bond curves for beams 65, 66 and 67 shown in Figure 6.

Values of bond developed in the beam tests were calculated from the elongations of the lower rods, using the following formula:

$$B = r\ d\ E \div 8\ l\ L$$

where $B =$ bond (lbs/in^2),
$r =$ corrected dial reading [$=$ (dial reading $+$ zero correction) x 1.04] (ins.),
$E =$ modulus of elasticity of steel (lbs/in^2),
$d =$ diameter of rod (ins.),
$L =$ gage length of extensometer (ins.),
$l =$ length of embedment of rod (ins.),

As the radius of the wire increased the length of the path around the dial drum by about 4 per cent. the quantity 1.04 was used in computing r in the above formula to correct for the thickness of the wire.

The modulus of elasticity used in computing the bond in beams 1 to 64 was 30,000,000 lbs/in^2 and in beams 65 to 67 28,600,000 lbs/in^2.

The stress in the rod was computed from the following formula:

$$S = \frac{Er}{2L}$$

Where $S =$ the stress in the steel (lbs/in^2) and the other quantities are the same as before.

In testing the bond cylinders the rod was run up through the pulling head of the testing machine and gripped in the upper head. Blotting paper was placed between the top of the cylinder and the lower face of the pulling head to equalize the effect of any irregularities on the surface of the cylinder. A speed of .05 or .15 of an inch per minute was used in applying the load on the specimen. After testing, the cylinders were broken open, the length of embedment checked, and any flaws or defects on the surface of the rod noted.

The bond in cylinder tests was found by dividing the pull on the rod by the area of the surface embedded. For the ½-inch

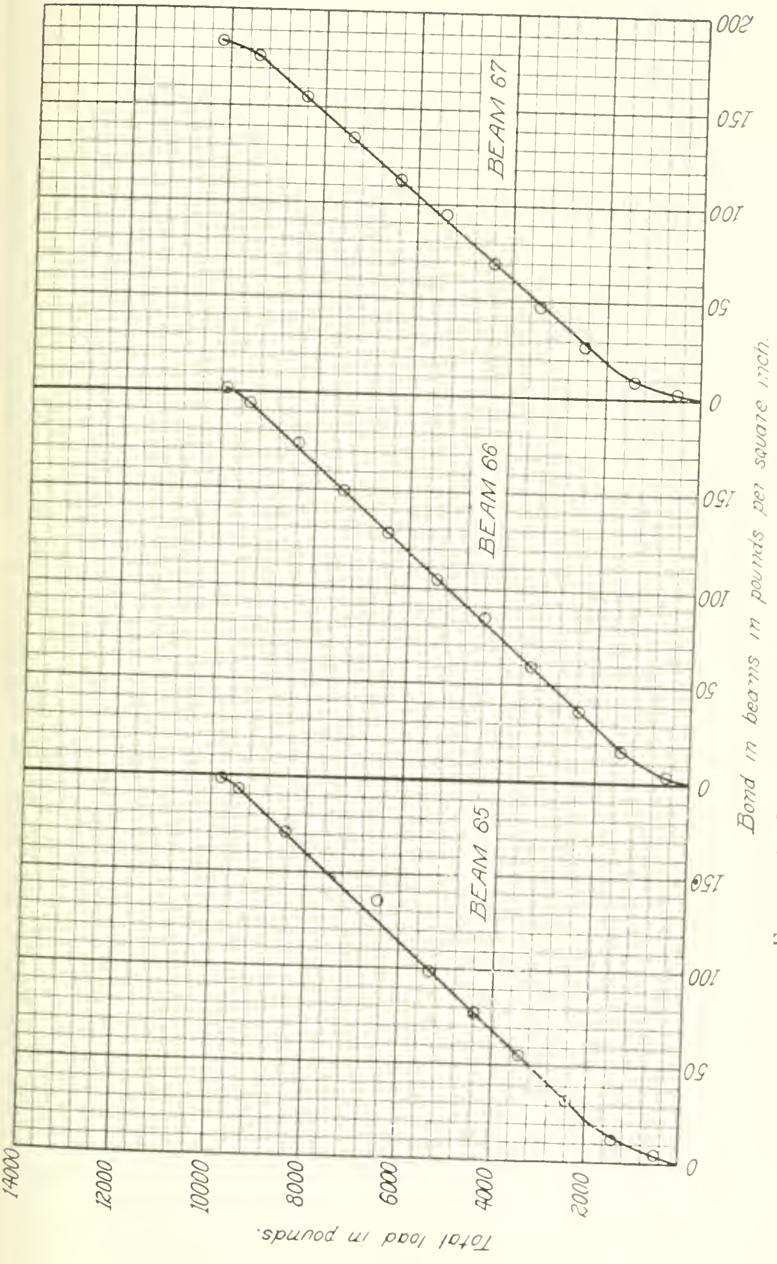


FIGURE 6.—LOAD—BOND CURVES FOR BEAMS 65, 66 AND 67.

corrugated bars with 10-inch embedment the divisor used was 20.

1. Effect of Age on Bond

Table VII contains the results of 15 beam tests to determine the effect of age upon the bond between 1: 2: 4 concrete and ⅝-inch round steel rods. These beams were loaded as shown in Figure 2a. The variables in age were 7, 28, 60 days and 6 months. Although there is a considerable variation from the mean at some of the ages, the average bond increased with the age of the specimen. This is well shown by the age-bond curve in Figure 7 drawn through these plotted averages. The curve shows that a bond of 253 lbs/in^2, or 80 per cent of the bond at 6 months, was developed when the specimens were a month old.

2. Bond of Different Mixes

A comparison of the bonds of several mixes of different proportions is given in Table VIII. Nine beams were loaded as shown in Figure 2a and tested. The bond developed with the 1:3:6 mixture was decidedly lower than those obtained with the others mixes. There was very little difference in the average bonds of the 1:2:4 limestone, 1:2:4 gravel and 1:2½ mortar. The results indicate that the bond is directly affected by the richness of the mortar but not materially by the kind of stone, providing pockets are prevented from forming around the reinforcement.

3. Effect of Consistency on Bond

Nine beams of 1:2:4 concrete with lower rods ⅝-inches in diameter were tested under loads placed as shown in Figure 2a to determine the effect of consistency on bond. Table IX contains the results of these tests. The averages in the table indicate that the amount of water used had no decided effect on the bond when the specimens were 60 days old. It is probable that the hard ramming to which the dry beams, 29, 30 and 31, were subjected considerably raised the bond in these beams.

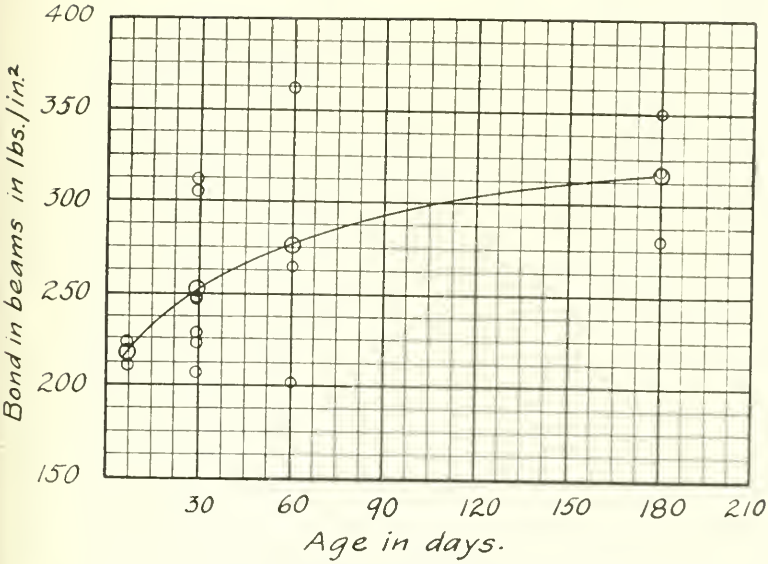


FIGURE 7.—EFFECT OF AGE ON BOND.

TABLE VII.

TESTS ON BOND IN BEAMS STATICALLY LOADED. EFFECT OF AGE ON THE BOND BETWEEN 1:2:4 CONCRETE AND $\frac{5}{8}$-IN. ROUND RODS.

Beam No.	Maximum load, lbs.	Age.	Stress in steel lbs., in.²	Bond lbs./in.²	Compressive strength of concrete lbs./in.²
1	4.000	7 da.	14.200	222	
2	3.400	"	13.500	211	
Average		"		216	1.400
4	6.800	28 da.	23.000	305	
5	4.400	"	19.200	312	2.030
6	4.600	"	12.900	207	
54	4,500	"	14,500	228	
55	4.500	"	15.900	248	
56	4.300	"	14.100	222	1.690
57	5.000	"	16.300	247	
Average		"		253	1.860
7	4.800	60 da.	18.500	362	
8	4.200	"	16.900	264	
9	4.000	"	11.100	201	
Average		"		276	1.790
10	4,200	6 mos.	17.900	280	
11	5.200	"	21.300	350	
12	4.800	"	19.800	318	
Average		"		316	1.630

TABLE VIII.

TESTS ON BOND IN BEAMS STATICALLY LOADED.

Comparison of the bonds between various mixes and ⅝-in. round rods. Age 60 days.

Beam No.	Mix.	Maximum load lbs.	Stress in steel lbs/in^2	Bond lbs/in^2	Compressive strength of concrete lbs/in^2
7	1:2:4	4,800	18,500	362	
8	"	4.200	16,900	264	
9	"	4.000	11,100	201	
Average	"			276	1,790
17	1:3:6	3,200	11.600	181	
18	"	4,400	18,100	251	
Average	"			216	830
19	1:2:4 g.	5,200	19.900	282	
20	"	4,800	17,200	269	
Average	"			275	2,200
21	1:2½	3.600	16.600	235	
22	"	3,800	18,200	300	
Average	"			267	1,600

TABLE IX.

TESTS ON BOND IN BEAMS STATICALLY LOADED.

Effect of different consistencies on the bond between 1 : 2 : 4 concrete and ⅝-in. round rods.

Beam No.	Consistency.	Maximum load lbs.	Stress in steel lbs/in^2	Bond lbs/in^2
23	Wet.	3,200	11,000	180
24	"	4,800	22,100	346
25	"	4,000	16.500	224
Average	"			250
26	Medium.	3,200	11,800	171
27	"	3,600	18.500	321
28	"	3,500	13,600	212
Average	"			235
29	Dry.	4,800	19,300	287
30	"	3.600	20.100	314
31	"	3,600	13,600	224
Average	"			275

Age of specimens 60 days.

4. Effect of Size of Rod on Bond

Three beams were made with each of the following sizes of lower rod $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, $\frac{3}{4}$ and 1-inch, and tested under loads as shown in Figure 2a. Beams 65, 66 and 67, 9 feet long, 6 inches wide and 8 inches deep and reinforced with lower rods 1 inch in diameter were loaded as shown in Figure 2d and tested. It appears from Table X, which gives the results of these tests, that the bond between 1:2:4 concrete and rods $\frac{3}{8}$ to $\frac{3}{4}$ inches in diameter is practically constant. The bond in both sets of specimens containing 1-inch rods was decidedly less than it was in the specimens with the smaller rods. From these tests it would appear that the bond between concrete of this class two months old, and plain round rods less than $\frac{3}{4}$-inch in diameter is 200 to 250 lbs/in^2. For 1-inch rods the bond is 175 to 200 lbs/in^2.

TABLE X.

Tests on Bond in Beams Statically loaded.

Effect of size of rod on the bond of 1: 2: 4 concrete.

Age 2 mos.

Beam No.	Size of rod ins.	Maximum load lbs.	Stress in steel lbs/in^2	Bond lbs/in^2
38	$\frac{3}{8}$	3.200	27.600	345
30	..	3.400	23.800	298
40	..	2.400	16.700	190
Average				278
41	$\frac{1}{2}$	4.400	26.400	361
42	..	3.600	21.200	312
43	..	2.800	12.300	186
Average				286
7	$\frac{5}{8}$	4.800	18.508	362
8	..	4.200	16.900	264
9	..	4,000	11.100	201
Average				276
44	$\frac{3}{4}$	5.000	12.400	207
45	..	4.400	13.900	289
46	..	6.200	15.700	295
Average				264
47	1	3.400	5,850	136
48	..	4.000	7.650	174
49	..	4.000	7.900	180
Average				163
65	1	9.800	25,500	199
66	..	9.900	25.800	202
67	..	10,200	23,600	184
Average	..			195

5. Effect of Various Methods of Loading on Bond in Beams

Beams 54 to 61 were made to determine the effect on bond of embedding the rod in stressed and unstressed concrete. Beams 54 to 57 were made and loaded as shown in Figure 2a. Figure 2c represents beams 58 to 61. The results given in Table XI apparently indicate that the bond of concrete subjected to a tensile stress is greater than that of concrete which is practically unstressed. This difference in bond may have been caused partly by the difference in strength of the concrete in the two sets of beams.

TABLE XI.

Tests on Bond in Beams Statically Loaded.

Effect of various methods of loading. Age of 1:2:4 concrete 1 mo.

⅝-in. round rods.

Beam No.	Maximum load lbs.	Stress in steel lbs /in ²	Bond lbs/ in ²	Compressive strength of concrete lbs/ in ²
54	4.500	14.500	228	
55	4.500	15.900	248	
56	4,300	14,100	222	
57	5 000	16,300	247	
Average	....	....	236	1,690
58	3.400	8,800	129	
59	3.300	9.500	141	
60	4.100	12,600	187	
61	3,900	13,700	204	
Average	....	....	165	1,070
62	6.850	19,000	197	
63	6.800	20,300	215	
64	7,000	22,100	236	
Average	....	....	216	2,315

Beams 62, 63 and 64 were designed to determine the effect of a change from the standard loading, shown in Figure 2a. They were made and loaded as shown in Figure 2b. The average bond in these beams was not materially less than that obtained from beams 54 to 57. The small decrease in bond in beams 62, 63, 64 might have been due to the fact that they were sprinkled more frequently while curing than the other beams as this would tend to decrease shrinkage of the concrete and therefore lessen the bond.

6. Effect of Various Methods of Testing on Bond in Cylinders

Table XII contains the results of the tests on 8 bond cylinders all made from the same batch of concrete. A ¾-inch steel plate with a 1⅝-inch hole was placed between the upper surface of the cylinder and the lower face of the pulling head in testing bond cylinders 1, 2 and 3. Bond cylinders 4 and 5 were tested in the ordinary way with their upper surfaces bedded on blotting paper against the lower face of the pulling head. In both of the above sets of tests the concrete around the rod was in compression. Bond cylinders 6, 7 and 8 were made as shown in Figure 3b. Two rods were placed with axes coinciding with the axis of the cylinder, a smooth dowel pin fitting into the end of each serving to keep them in line while the molds were being filled. In testing, the projecting ends of the rods were gripped in the upper and lower heads of the machine and a load applied. In these tests both concrete and rod were in tension.

TABLE XII.

Comparison of Various Methods of Making Cylinder Tests on Bond.

Rods ⅝ in. round. Concrete 1:2:4. Age of specimens 28 days.

Cylinder No.	Method of testing.	Maximum load lbs.	Embedment ins.	Bond lbs/in²
1	Concrete in compression. Steel plate cap.	6,025	11¼	279
2		7,450	12⅛	312
3		10,275	12¼	426
Average				339
4	Concrete in compression. Pulled against head of machine.	6,420	12¼	266
5		9,150	12	387
Average				327
6	Concrete in tension. Two rods embedded with ends in contact at center of cylinder.	4,700	12⅛	197
7		4,600	12¼	191
8		4,430	12	188
Average				192

These tests show conclusively that the kind of stress to which the concrete surrounding a plain rod is subjected exercises a great influence on the bond. The average bond in cylinders 1 to 5 was 68 per cent. greater than in cylinders 6, 7 and 8. The average value for 6, 7 and 8, 192 lbs/in^2, is somewhat lower than values obtained from tests of beams 54 to 57.

7. COMPARISON BETWEEN BEAM AND CYLINDER TESTS ON BOND

A comparison between the bond developed in beams and that obtained from bond cylinders made from the same batches of concrete as the corresponding beams is afforded in Table XIII. The last column in the table is computed by dividing the pull on the rod of the bond cylinder by the area of the cylinder, no allowance being made for the area of the hole in the head of the testing machine. Figure 8 shows a curve plotted from the values in the last two columns of the table. The curve indicates that the ratio of bond in cylinder to bond in beam increased with the intensity of compressive stress applied to the top of the bond cylinder. While a longer embedment in the cylinder tests would probably decrease the difference in the results obtained from the two methods of testing and is doubtless the cause of the discrepancy in the 1-inch results, this table and figure show that the ordinary method of making bond tests, where the upper surface of the bond cylinder is in compression, gives values which are too high to use in designing reinforced concrete beams. In these tests the bond in cylinders ran from 1.42 to 2.99 times as large as that obtained from the corresponding beam tests. As special care was taken to make curing conditions as uniform as possible it is believed that the results are representative of the two methods of testing. Therefore reliable working values of bond for use in designing reinforced concrete beams and slabs, should be based upon the results of tests on bond in beams where the conditions are comparable with those in the structure.

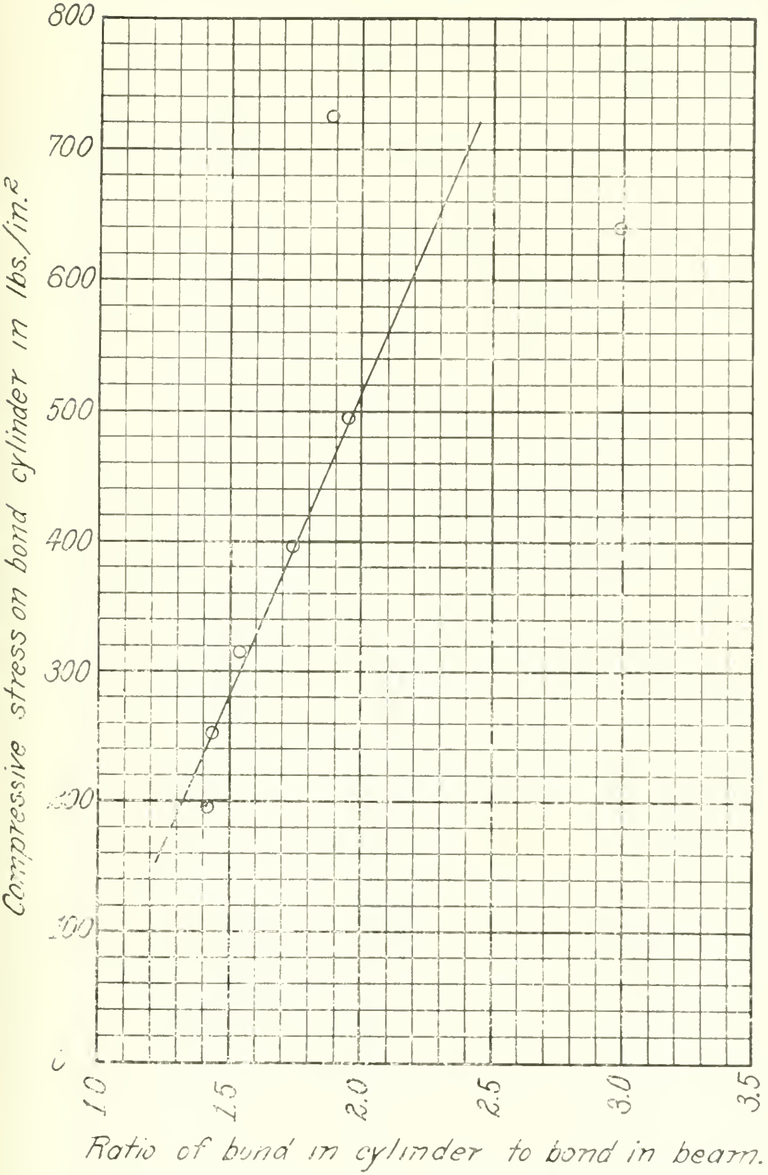


FIGURE 8.—RELATION BETWEEN BEAM AND CYLINDER TESTS.

TABLE XIII.

Static Bond Tests.

Comparison of results obtained from beams and cylinders.

Beam No.	Size of rod ins.	Average bond in beam lbs/in²	Average bond in cylinders lbs/in²	Bond in cyl. / Bond in beam.	Compressive stress on top of bond cyl. bs/in²
38-39-40	⅜	278	394	1.42	197
41-42-43	½	286	455	1.54	317
62-63-64	⅝	216	311	1.44	252
36-37	⅝	266	467	1.76	395
44-45-46	¾	264	502	1.90	495
47-48-49	1	163	487	2.99	620
65-66-67	1	195	367	1.88	725

TABLE XIV.

Summary of tests on the Bond between Concrete and Steel Rods Subjected to Static and Repeated Loadings.

Concrete 1:2.2:4.4. Age of specimens 1 month.

Beam No.	Size and kind of bar.	No. of repetitions of load.	Bond in beams lbs/in²	Bond in cylinders lbs/in²	Stress in steel lbs/in²	Compressive strength of concrete lbs/in²
A1	½-inch corr....	....	311	525	24,900	1,380
A2	½-inch corr....	*104.500	245	... .	19.600	....
A3	⅝-in. p. round.	....	143	....	9.200	....
B5	½-inch corr....	....	424	....	33.900	1,480
B6	½-inch corr....	2,000	320	....	25.600	....
B7	⅝-in. p. round.	*1,000	80	....	5.200	....
B8	⅝-in. p. round.	....	93	....	6.000	....
C9	½-inch corr....	*46.000	285	705	22.800	1.420
C10	½-inch corr....	....	402	....	32,200	1,310
C11	⅝-in. p. round.	....	210	408	13.500	....
C12	⅝-in. p. round.	7.000	130	....	8.400	....
D13	½-inch corr....	....	361	....	28.900	1,170
D14	½-inch corr....	26.000	285	....	22.800	....
D15	⅝-in. p. round.	53.100	145	401	9.300	....
D16	⅝-in. p. round.	....	244	387	15,700	....
E17	½-inch corr....	....	545	....	43.600	1,740
E18	½-inch corr....	*31,500	355	....	28.300	....
E19	⅝-in. p. round.	....	185	300	11.900	....
E20	⅝-in. p. round.	*66.000	125	....	8.000	....
F21	½-inch corr....	....	526	....	42.100	1.880
F22	½-inch corr....	*15.400	345	....	27.600	....
F23	⅝-in. p. round.	1,200	155	342	10.000	....
F24	⅝-in. p. round.	*40,000 12.000	150 200	....	9.700 12.800	....
G25	½-in. r. round.	3.200	270	374	21.600	1.380
G26	½-in. r. round.	....	399	....	32,000	....
G27	⅝-in. r. round.	....	260	....	16,700	....
G28	½-in. r. round.	1.700	205	....	16,400	....
H29	½-in. r. round.	*70.000	175	508	14,000	1,600
H30	½-in. r. round.	....	458	....	36,600	....
H31	½ in. r. round.	....	320	....	25.600	....
H32	½-in. r. round.	79,000	190	....	15.200	....

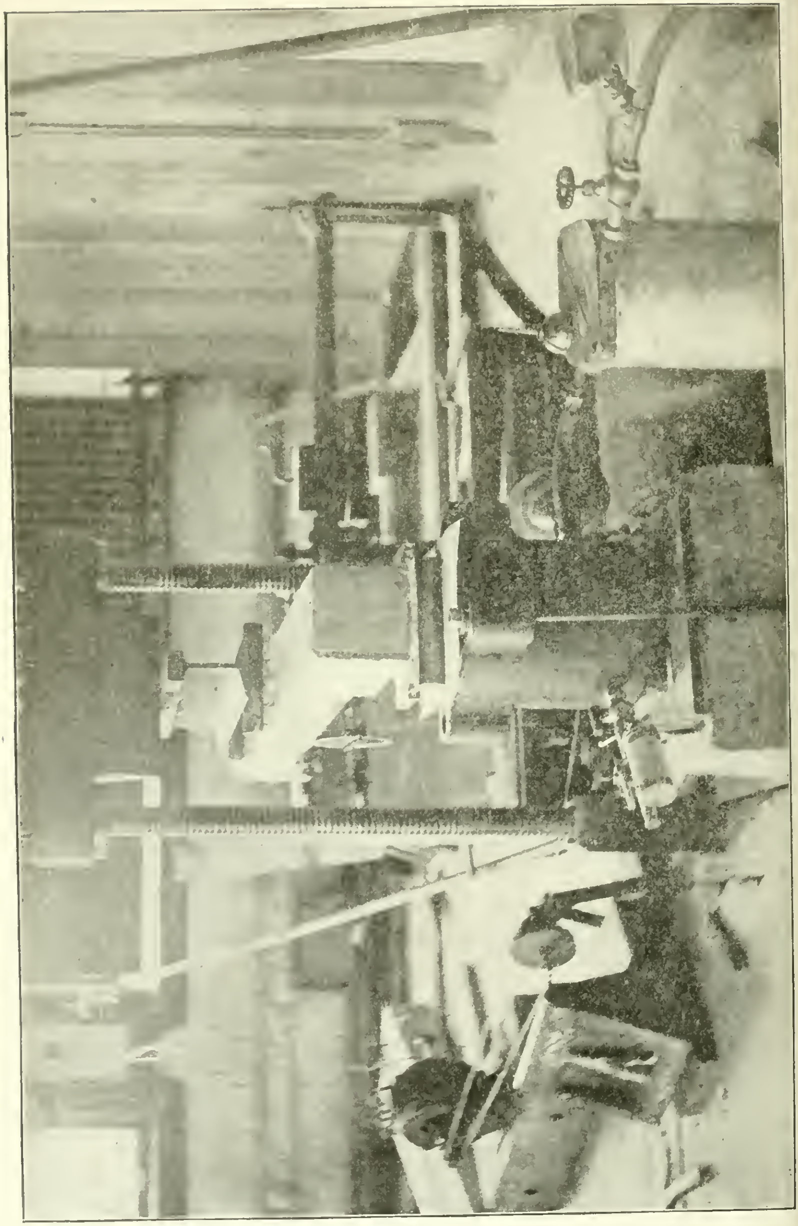
*Without failure.

V. TESTS OF BOND UNDER REPEATED LOADS

Table XIV contains a summary of the results of tests on bond in beams subjected to repeated loadings. The size of beam, method of loading, etc., used in this series of tests, is shown in Figure 2a. Tests were made on plain round rods, rusted round rods and corrugated bars.

Method of Testing and Computation. About half of each class and batch of beams was tested under static loadings so that an estimate of the strength of the others to be tested under repeated loadings could be made. These static tests were conducted in practically the same manner as previously described, the only exception being the method of applying loads, which was accomplished by means of the plunger operated by air pressure, shown in Plate II. The pressure on the plunger was added in 5 lbs in^2 increments (measured on the indicator card) and the corresponding elongations of the lower rod were read.

For the repeated tests, an elongation was calculated from the static test made from the same batch which would produce a given bond between the concrete and lower rod. The beam which was to be tested under repeated loads was then loaded statically until the elongation of the lower rod equalled this predetermined amount. The air pressure producing this elongation was noted and used in applying the repeated loads. Owing to the increase in elongation of the lower rod after a few thousand repetitions, caused by formation of tension cracks in the concrete, the elongation at the start was made slightly less than the value finally desired. After making a determination of the proper air pressure to use, the rotating valve was started and this pressure maintained for 500 or 1,000 repetitions of load, when the motor driving the valve was stopped and another static loading applied. If the elongation for the pressure which was being used in the repeated tests differed materially from that desired, the pressure was adjusted to produce the desired elongation and 1,000 or 2,000 more loads applied. Another static loading was then imposed, after which the repeated load-



[illegible] II.—[illegible] Repeating Loads ings were continued. When it became evident that the required elongation was being produced by a practically constant air pressure, the intervals between stops were made longer. Generally a constant air pressure was used throughout the repeated tests on any one beam and was applied 100 times per minute.

In calculating the bond in all beams of this series, no allowance was made for any zero correction. In general, owing to the method of applying the loads, this correction, if made, would be considerably smaller than that applied to beams 1 to 49. Considering the nature and purpose of the tests and the difficulty in introducing an accurate correction in all cases, it was decided to disregard it. In computing bond in beams, the average modulus of elasticity for each of the different sizes below the black line in Table IV was used.

In computing the bond in beams subjected to repeated loadings, the results in column 4 of Table XIV were obtained from the repetition-elongation curves, most weight being given to the high values in computing these averages. In Tables XV, XVI, and XVII, column 7 was computed by dividing the results in column 4, Table XIV, by the average of column 4 in the table being computed. Columns 5 and 6 show the limits between which the percentage of static bond employed varied during any repeated test. These values were computed from the lowest and highest values of elongation shown on the repetition-elongation curves. No attempt has been made to figure the actual bond between concrete and steel when the beam was broken under repeated loads. An estimate of this can easily be made from the repetition-elongation curve, if desired. With the exceptions mentioned above, the method of computing bond in the cylinder and beam tests of this series was the same as that outlined under static bond tests.

From the beams of this series tested statically, air pressure-elongations curves have been plotted and are shown in Figures 11, 16, 20 and 21. Some of the air pressure-elongation curves obtained during the tests of beams subjected to repeated loadings are shown in Figures 12 to 15, 17 to 19 and 22 to 26. Those curves obtained after a number of repetitions are more nearly straight than those obtained at the initial loading. This is due to the fact that the formation of tension cracks in the concrete caused the steel to carry practically all the tensile stress in the beam.

The repetition-elongation curves for these beams are also given in the same figures. Vertical lines in these curves indicate an increase in pressure. In general, as may be seen from these curves, (Figure 23, for example) the deformation increased quite rapidly during the first few thousand repetitions at constant air pressure, caused by the increased tension in the steel due to tension cracks in the concrete. After this, conditions became more constant and the curve more nearly horizontal. The repetition-elongation curves for beams containing round rods which failed under repeated loadings show a quite steady decrease in elongation before failure, probably caused by a slight slipping of the rod.

1. Plain Round Rods

Beams A3, B7, B8, C11, C12, D15, D16, E19, E20, F23 and F24 contained ⅝-inch plain round rods. It is quite probable that the rods in beams B7 and B8 came in contact with the oiled forms before the beams were poured. Consequently the results from these beams are not considered of sufficient importance to be tabulated in Table XV. As batch B was the only one in which the forms were oiled, no trouble from this source was experienced in tests of the other beams. As no repetition test was made from batch A, beam A3 is also omitted from the table.

The following record of the test of beam D15 illustrates the behavior of a beam of this set which failed under repeated loads. After 1,500 repetitions, concrete had spalled off slightly where the bond rod entered the concrete, indicating a failure in bond at that point. No cracks parallel to the bond rod were visible throughout the test. After the load had been repeated 46,500 times, a sharp snapping noise which appeared to come from the end of the beam was heard each time the load was released. It will be observed also that the elongations in the repetition-elongation curve, Figure 13, showed a decided decrease at this time. A higher pressure was then employed to increase the elongation

TABLE XV.

RESULTS OF TESTS ON THE BOND BETWEEN CONCRETE AND ⅝-IN. PLAIN ROUND RODS SUBJECTED TO STATIC AND REPEATED LOADINGS.

Concrete 1:2.2:4.4. Bars ⅝-in. round. Age of specimens 1 month.

Beam No.	Compressive strength of cylinder lbs in²	Static bond lbs in²		Repeated loading.			
				Per cent of static bond employed.			No of repetitions.
		Cylinder test.	Beam test.	Low.	High.	Average.	
1	2	3	4	5	6	7	8
C11	1420	408	210	....	....	....	....
C12	1310	....	....	54	67	61	7000
D16	1170	401	244	....	....	....	....
D15	....	387	....	53	76	68	53100
E19	1740	300	185	....	....	....	....
E20	....	....	*216	50	70	58	*66000
F23	1880	312	....	38	82	72	1200
F24	....	....	....	63	71	70	40000
F24	....	....	....	71	103	93	12000
Av.......	1504	368	214	....	....	....	....

*Beam after withstanding the number of repetitions indicated in col. 8 was broken under static loading, see col. 4.

in the rod. Shortly after this, the same snapping was observed at the other end of the beam. An examination of the bar showed it had slipped throughout its entire embedment. (The frictional resistance developed after the bar slipped was 146 lbs in²).

Beam E20 withstood 66,000 repetitions of a bond stress averaging 125 lbs in² without failure. It was then loaded statically and the bar slipped when the bond was 216 lbs in².

From the results in Table XV, the appearance of the repetition-elongation curves and the behavior of the beams tested under repeated loads, it would appear that a bond of 50 or 60 per cent. of the ultimate static bond can be repeated a very large number of times without failure in bond. For the beams tested, this repetition limit would be 107 to 128 lbs in².

A comparison between the static bond developed in the beam and cylinder tests of this set confirms the results from tests made in connection with beams 36 to 67.

2. Rusted Round Bars

The eight beams of batches G and H contained rusted round rods. Results of tests of seven of these beams with ½-inch rods are given in Table XVI. Results of the test on beam G27 are omitted because the diameter of the rod was ⅝ of an inch, and the bond was decidedly lower than that obtained from any of the other beams of this set.

TABLE XVI.

Results of Tests on the Bond Between Concrete and ½-in. Rusted Round Rods Subjected to Static and Repeated Loadings.

Concrete 1:2.2:4.4. Age of specimens 1 month.

Beam No.	Compressive strength of cylinder lbs in²	Static Bond lbs in²		Repeated loadings.			
				Per cent of Static Bond employed.			No. of repetitions.
		Cylinder test.	Beam test.	Low.	High.	Average	
1	2	3	4	5	6	7	8
G26	1,380	374	399	....	....	....	....
G25	....	....	....	52	70	69	3,200
G28	....	....	....	43	59	52	1,700
H30	1,600	508	458	....	....	....	....
H31	....	....	320	....	....	....	....
H29	....	....	*390	38	48	44	*70,000
H32	....	....	....	43	51	48	79,000
Av.......	1,490	441	392				

* Beam after withstanding the number of repetitions indicated in col. 8 was broken under static loading, see col. 4.

The behavior of these beams while being tested was similar to that of the beams containing plain round rods. The values of the bond developed in these beams containing rusted round rods were decidedly higher than those obtained from beams reinforced with plain round rods. The difference in size of rods employed in the two sets of beams could not have greatly affected the results as the cylinder bond test on a plain round ½-inch rod made with batch G showed a bond of only 296 lbs in², and the one with batch H, 390 lbs in², while the results from cylinders with rusted bars, given in the table, are considerably higher.

From the small number of beams tested it is not possible to draw conclusions which will apply to rods of different sizes and more or less rusted. It is evident from the tests, however, that the bond between concrete and a bar covered with a firm hard rust and subjected to either a static or repeated loading is considerably greater than that obtained from a plain round rod under the same conditions. In these tests the static bond between concrete and the ½-inch rusted round bars averaged 83 per cent. greater than the similar value from tests where ⅝-inch plain round rods were employed.

3. Corrugated Bars

The results of tests on beams reinforced with corrugated bars are tabulated in Table XVII. As beam A1 showed a much lower static bond than the other beams of this set the results from it are not included in the table. Elongation curves for these beams, Figures 22 to 26, show the initial rise in elongation produced by tension cracks in the concrete. Slight slipping of the bar probably produced the dips in the curves. This slight slipping was made evident, in the tests of the beams containing corrugated bars long before the ultimate bond was developed, by cracking of the concrete where the rod entered the beam and later in the test, by cracks parallel to the rod on the bottom of the beam. It is quite probable that this slipping did not take place over the entire length of embedment of the rod, at least not at the start, but was merely a loosening of the concrete where the rod entered the beam. That slipping progressed along the embedded length under the load applied seems evident from the crack on the bottom running parallel to the rod. Although this slight slipping momentarily lessened the stress in the rod, the lengthening of the tension cracks threw more stress back on the rod which, having been partially wedged in slipping, carried the load. Repetition of this procedure depended upon the firmness with which the bar was wedged in the concrete and the intensity of the pull in the rod. This wedging action was doubtless responsible for the cracks in the concrete on the bottom of the beam parallel to the rod.

TABLE XVII.

RESULTS OF TESTS ON THE BOND BETWEEN CONCRETE AND ½-IN. CORRUGATED BARS SUBJECTED TO STATIC AND REPEATED LOADINGS.

Concrete 1:2.2:4.4. Bars ½-in. sq. Age of specimens 1 month.

Beam No.	Compressive strength of cylinder lbs/in²	Static bond lbs/in²		Repeated loadings.			
				Per cent of static bond employed.			No. of repetitions.
		Cylinder test.	Beam test.	Low.	High.	Average.	
1	2	3	4	5	6	7	8
A2	1,380	525	*397	42	65	54	*104,500
B5	1,480	....	424	....	....	....	....
B6	....	....	....	63	72	71	2,000
C10	1,420	705	402	....	....	....	....
C9	1,310	....	....	57	65	63	†46,000
D13	1,170	....	361	....	....	....	....
D14	....	....	....	53	68	63	26,000
E17	1,740	....	545	....	....	....	....
E18	....	....	*521	64	81	78	*31,500
F21	1,880	....	526	....	....	....	....
F22	....	....	....	70	77	76	†15,400
Av......	1,483	615	454				

* Beam after withstanding the number of repetitions indicated in col. 8 was broken under static loading; see col. 4.
† Beam broken accidentally—valve stuck.

The record of the test of Beam A2 is characteristic of this set. After 4,000 repetitions with a 40 lbs/in² pressure concrete began to spall off around the rod where it entered the north end of the beam as shown in Figure 9a. After 7,000 repetitions a crack was noticed extending horizontally towards the side of the beam from the lower edge of the rod as shown in Figure 9b. After 70,000 repetitions a crack appeared extending vertically from the lower side of the bar to the bottom of the beam and running parallel to the bar along the bottom of the beam as shown in Figure 9c. After 78,000 repetitions a similar crack was observed at the south end of the beam which extended nearly to the support at 87,000 repetitions. No further signs of weakness nor extension of cracks was manifested. After 100,000 repetitions the air pressure was raised to 50 lbs/in². As 4,500 repetitions of this pressure produced no further signs of failure,

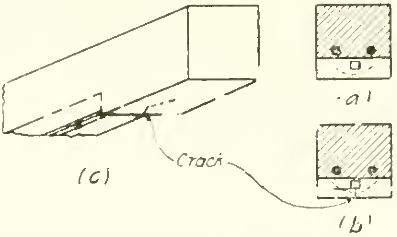


FIGURE 9. FORMATION OF CRACKS IN BEAMS REINFORCED WITH CORRUGATED BARS AND SUBJECTED TO REPEATED LOADINGS.

the beam was tested statically and failed when the bond was 397 lbs/in^2, nearly twice the average value employed during the repetition test.

Beams C9 and F22 were broken accidentally, due to sticking of the rotating valve during the absence of the experimenter. This caused the pressure to increase, as the air compressor kept on running, and finally broke the beam.

The final portion of the repetition-elongation curve of the beam D14, Figure 25, shows a rapid decrease in elongation due to slipping of the rod preceding final failure.

Typical failure cracks for this set of beams are shown in Plate III. In the right of the plate one can see how the concrete spalled off around the rod. The cracks in the bottom of the beams are also well shown. It is quite probable that the bond in these beams would have been increased somewhat if the rods had been placed farther from the bottom of the beam. Such increase would not have been great, however, as in many of the beams the rods were stressed nearly to their elastic limit. In fact beam E18 was stressed beyond the elastic limit under a static load without failure in bond after it had stood 31,500 repetitions at an average bond of 355 lbs/in^2.

From the results in Table XVII and the behavior of the beams tested, it is evident that 60 to 70 per cent. of the average static bond, about 270 to 320 lbs/in^2 in these tests, can be repeated a very large number of times without failure in bond. The bond between concrete and corrugated bars in beams tested statically

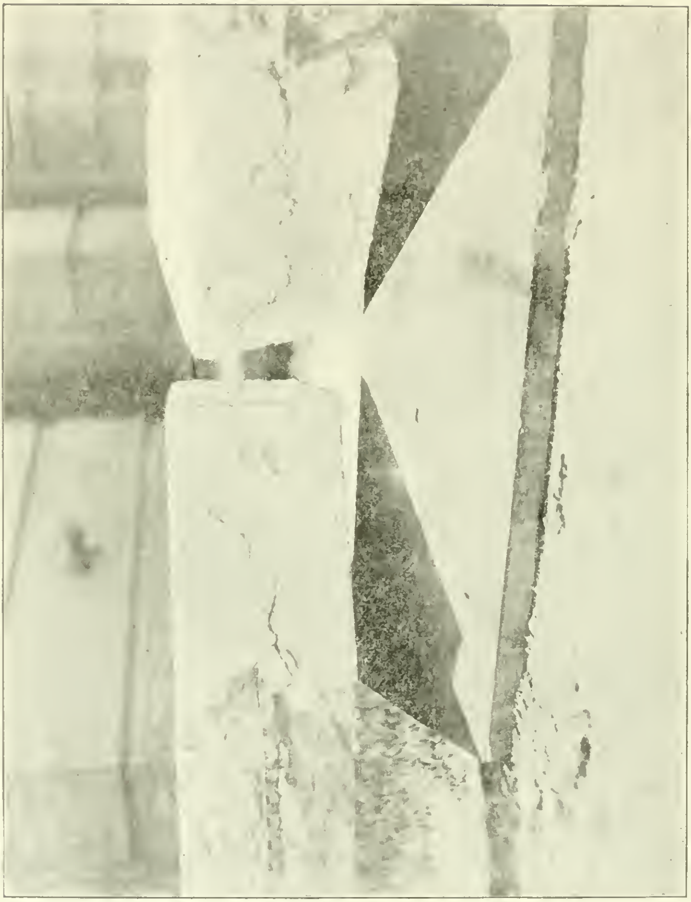


Plate III.—Typical Failure Cracks Caused by Repeated Loadings on Beams Reinforced with Corrugated Bars.

was about 2.1 times that obtained where plain and round rods were used and about 1.16 times that found in beams containing rusted round rods. The few cylinder tests made give values of bond averaging 36 per cent. higher than that computed from the beam tests. It will also be noted from the results in Table XVII that the bond in the static beam tests increases with the compressive strength of the batch. This without doubt results from the fact that both the bond of a deformed bar and the crushing strength of the concrete, are dependent upon the shearing strength of the concrete. Figure 10 contains a curve plotted with compressive strength of concrete as ordinates and static bond from beam tests as abscissae.

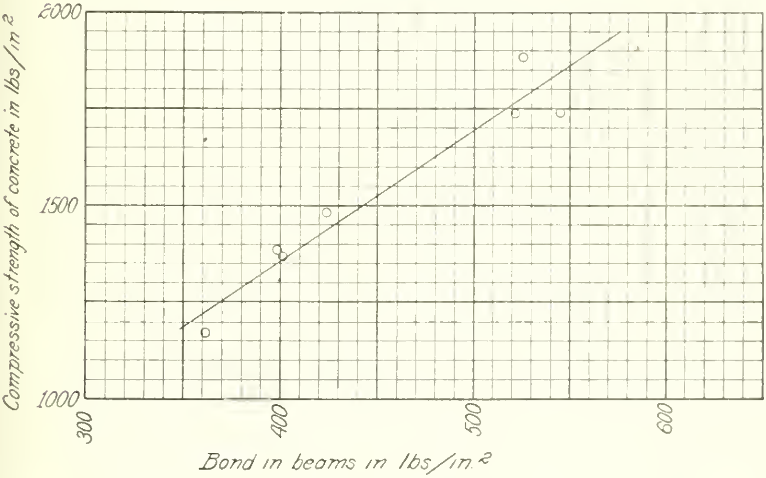


FIGURE 10.—RELATION BETWEEN COMPRESSIVE STRENGTH OF CONCRETE AND BOND BETWEEN CONCRETE AND CORRUGATED BARS.

VI. SUMMARY AND CONCLUSIONS

1. The static bond between 1:2:4 concrete and plain round steel rods increases with age at least up to six months. About 80 per cent. of the six months bond strength is developed in one month.

2. Owing to the variation in the results of individual tests and the difference between laboratory and practical working conditions, it does not seem as though the maximum static bond between concrete of the class used and plain rods less than ¾ inch in diameter should be assumed greater than 250 lbs/in^2 or for the rods of larger size 200 lbs/in^2.

3. The method of making bond tests by pulling a rod from a cylinder of concrete in such a manner that the concrete around the rod is compressed gives results which are neither of quantitative nor qualitative value. The results obtained are dependent largely upon the compressive stress acting on the head of the cylinder. Cylinder tests in which the rod and concrete are both subjected to a tensile stress give results more in accord with the bond values obtained from beam tests.

4. The beam test for bond, as herein described, approaches closely the actual condition to which the bar and surrounding concrete are most often subjected in beams and slabs, and gives results which are at least of qualitative value.

5. The static bond between the class of concrete employed and corrugated bars is about twice as great as that which can be developed with plain round rods of about the same size. The static bond between concrete and rusted rods is very much greater than that obtained where plain round rods are used.

6. The bond between concrete and corrugated bars increases with the compressive strength of the concrete. A similar relation does not appear in the results of tests of beams reinforced with round rods.

7. From the tests under repeated loadings it seems evident that 50 to 60 per cent. of the static bond between concrete and plain round rods may be repeated a large number of times with-

out failure in bond; that 60 to 70 per cent. are the corresponding figures for corrugated bars. Under repeated loadings the bond between concrete and rusted round rods is considerably greater than that between concrete and plain round rods.

8. Considering the severity of the tests made there seems to be no valid reason for believing that the bond between concrete and plain round rods will be destroyed under repeated loadings, providing a proper working value is used. Such a value for concrete of the class used in these tests should not be over 50 lbs/in^2.

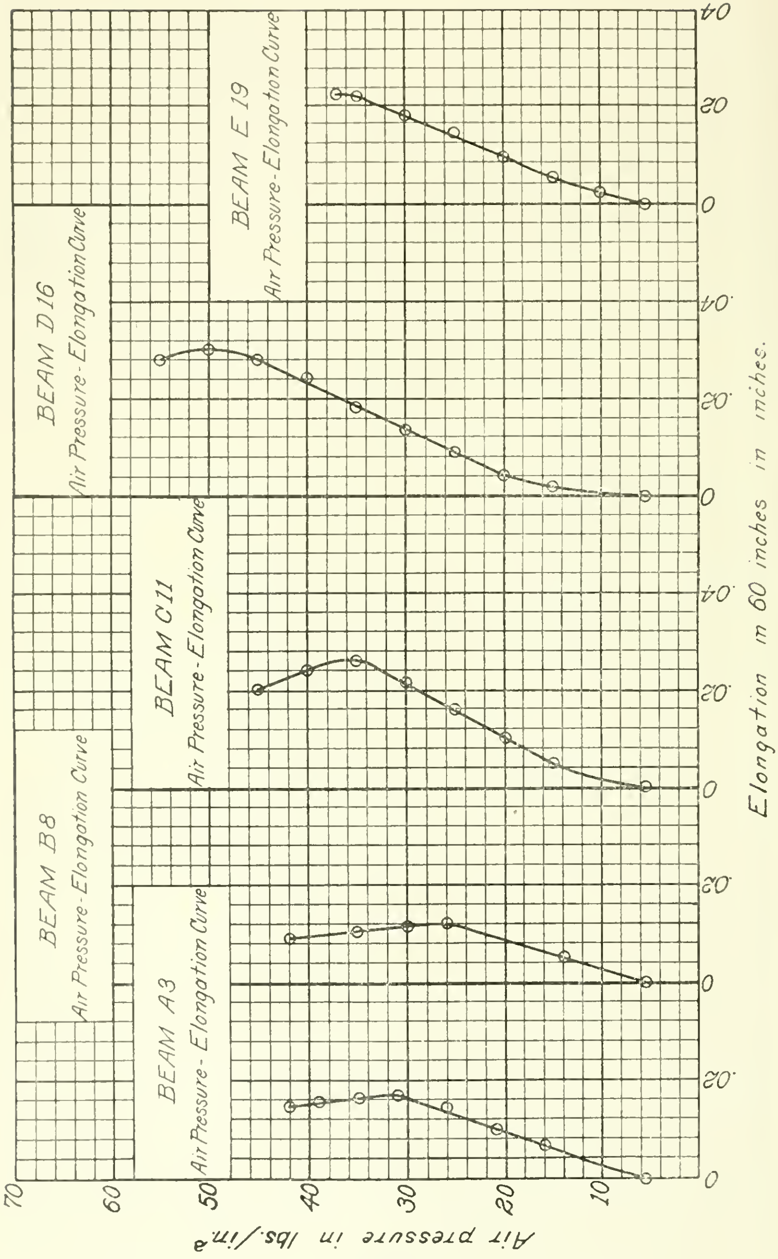


FIGURE 11.—BEAMS A 3, B 8, C 11, D 16, AND E 19—PLAIN ROUND RODS—STATIC TESTS.

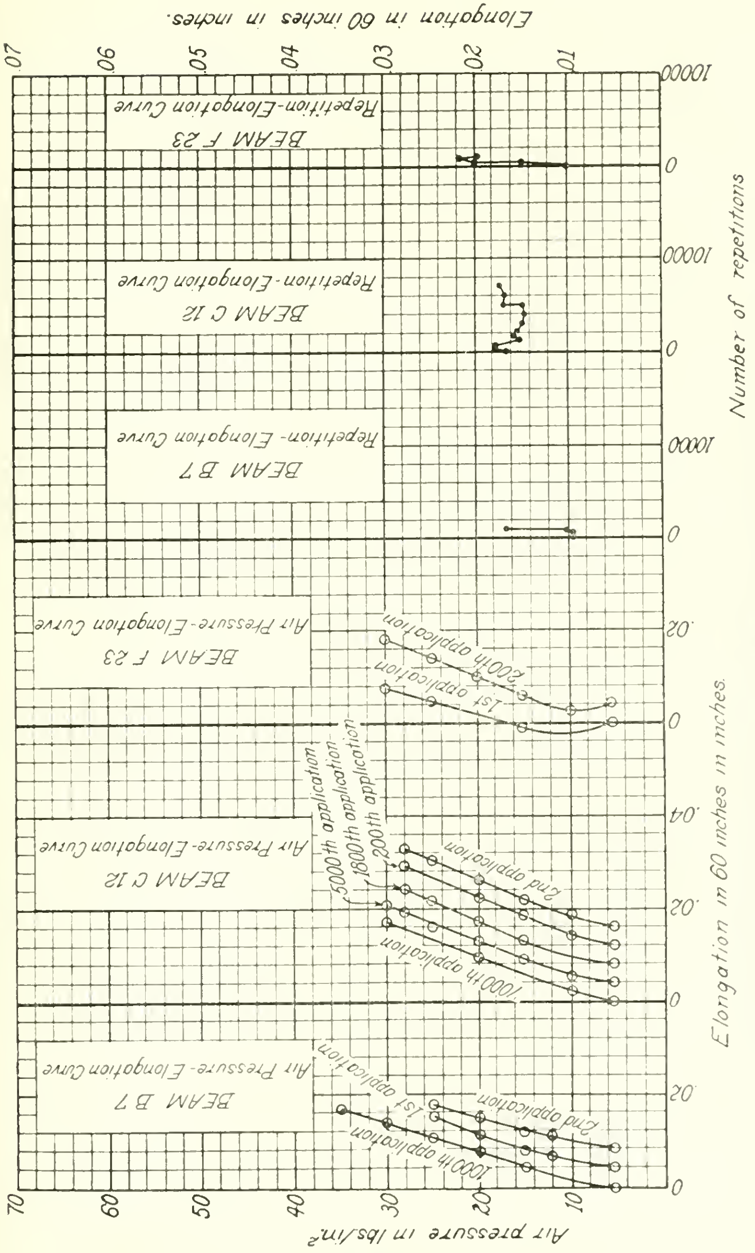


FIGURE 12.—BEAMS B7, C12, AND F23—PLAIN ROUND RODS—REPEATED TESTS.

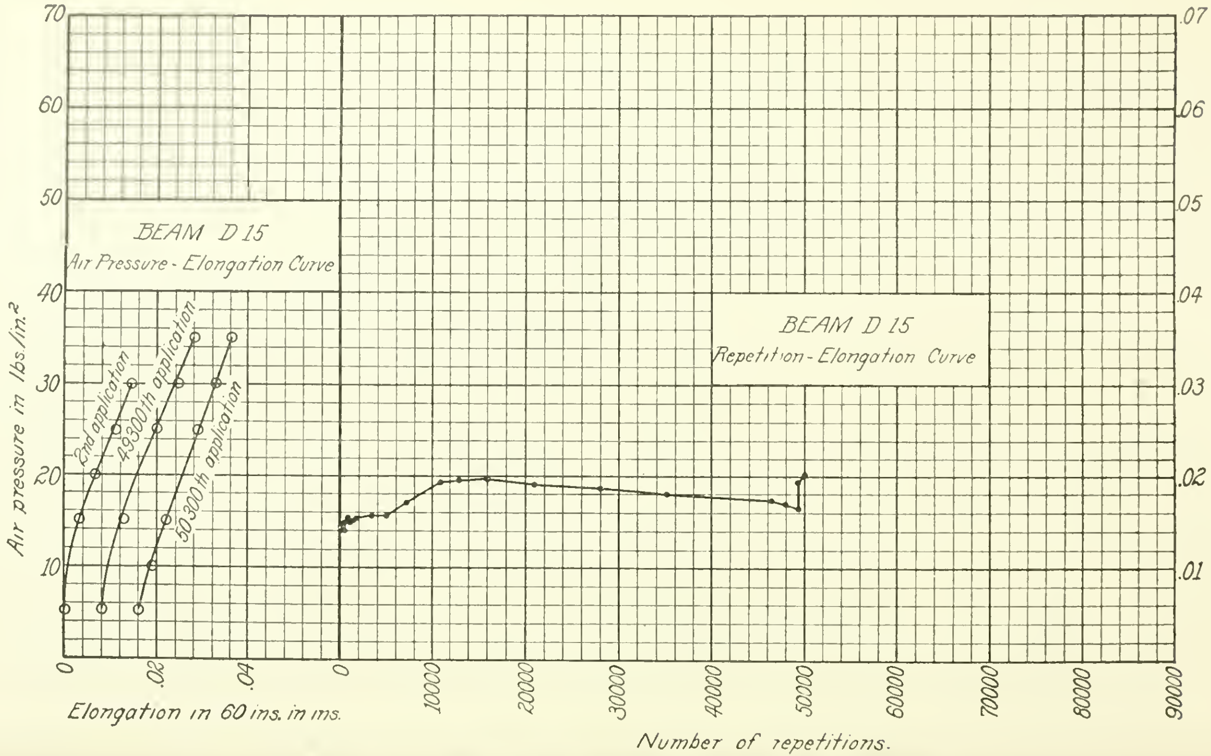


FIGURE 13.—BEAM D 15—PLAIN ROUND ROD—REPEATED TEST.

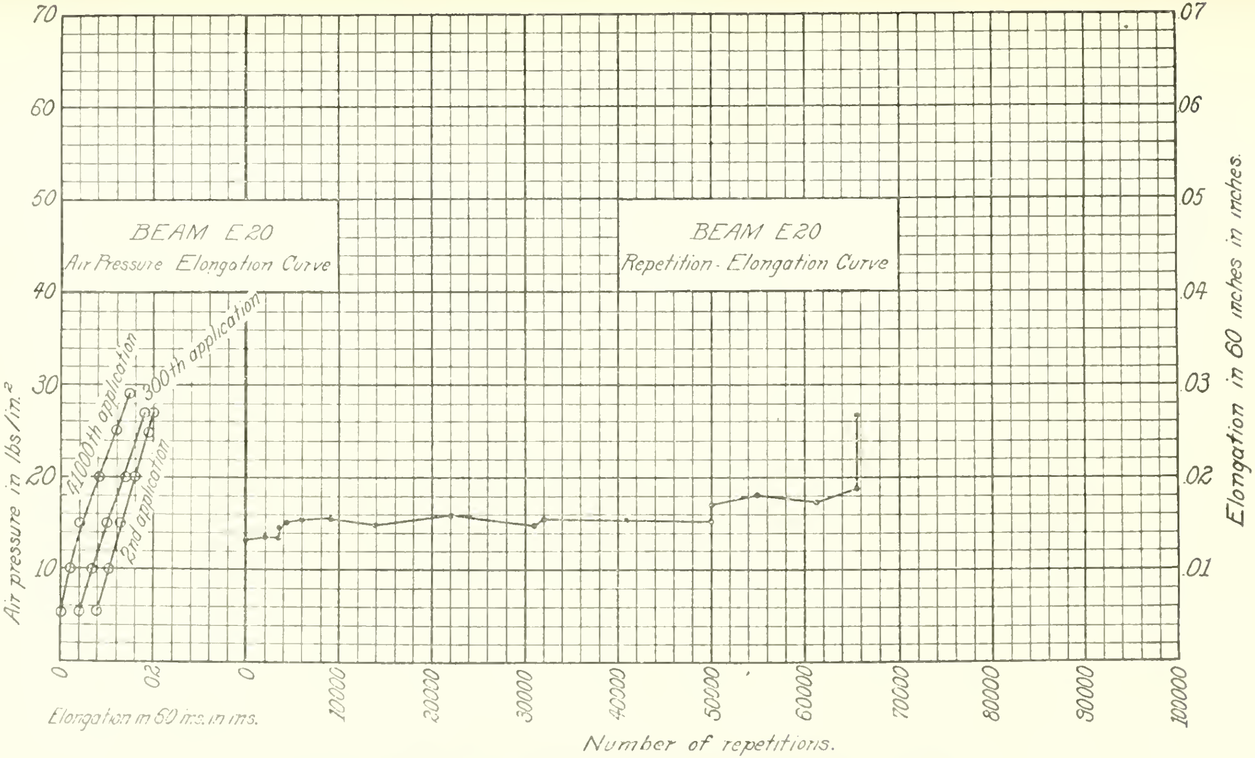


FIGURE 14.—BEAM E 20—PLAIN ROUND ROD—REPEATED TEST.

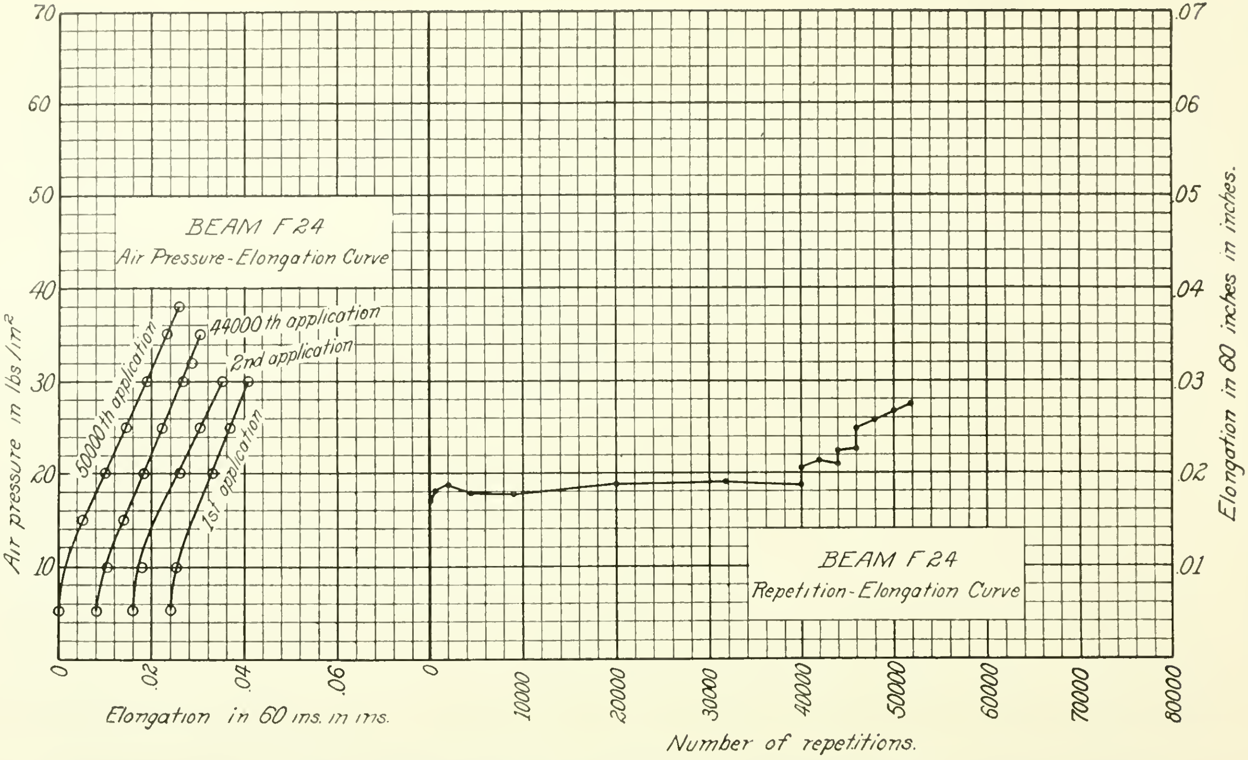


Figure 15.—Beam F 24—Plain Round Rod—Repeated Test.

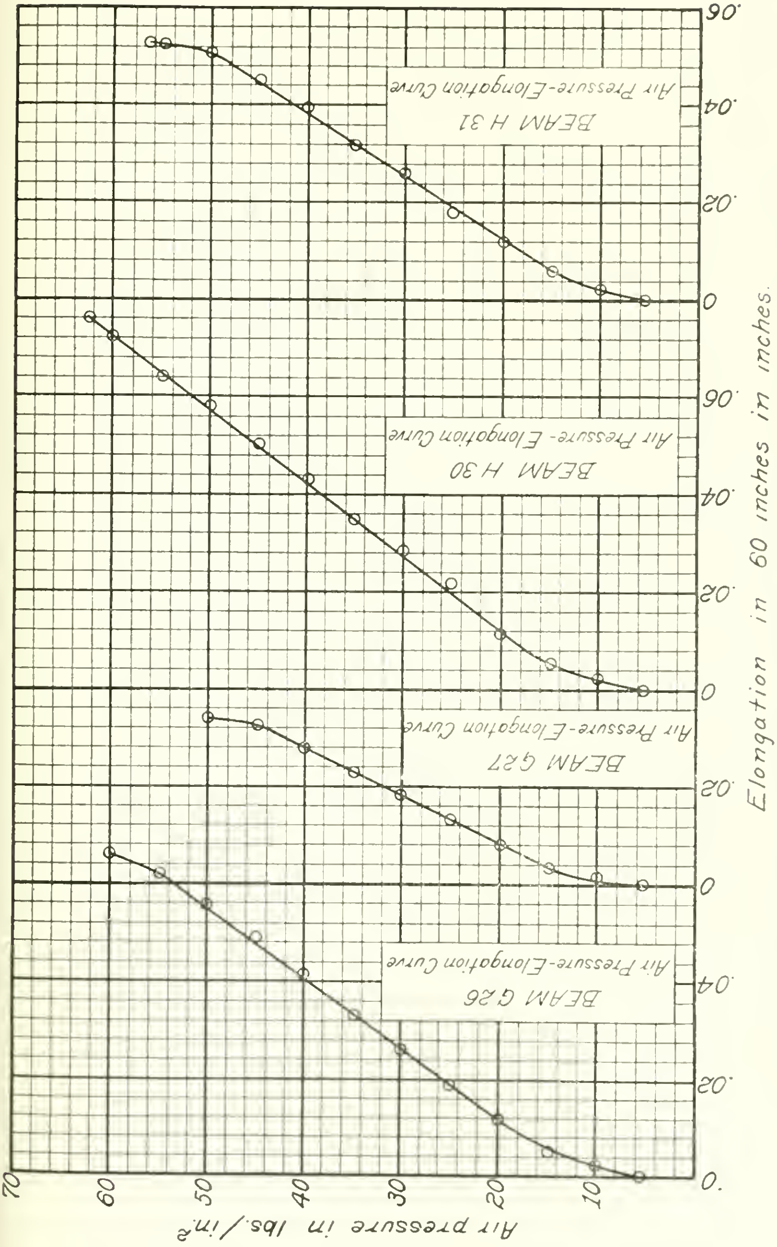


FIGURE 16.—BEAMS G26, G27, H30, AND H31—RUSTED ROUND RODS—STATIC TESTS.

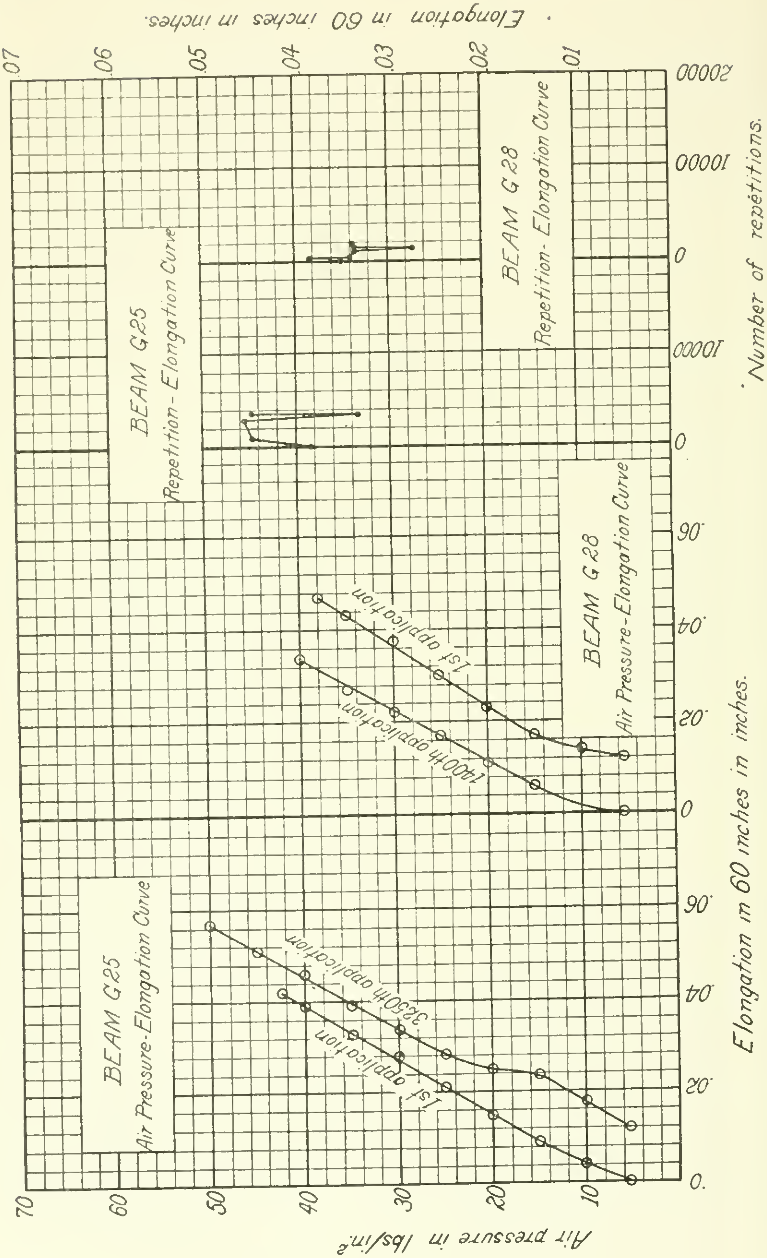


FIGURE 17.—BEAMS G 25 AND G 28—RUSTED ROUND RODS—REPEATED TESTS.

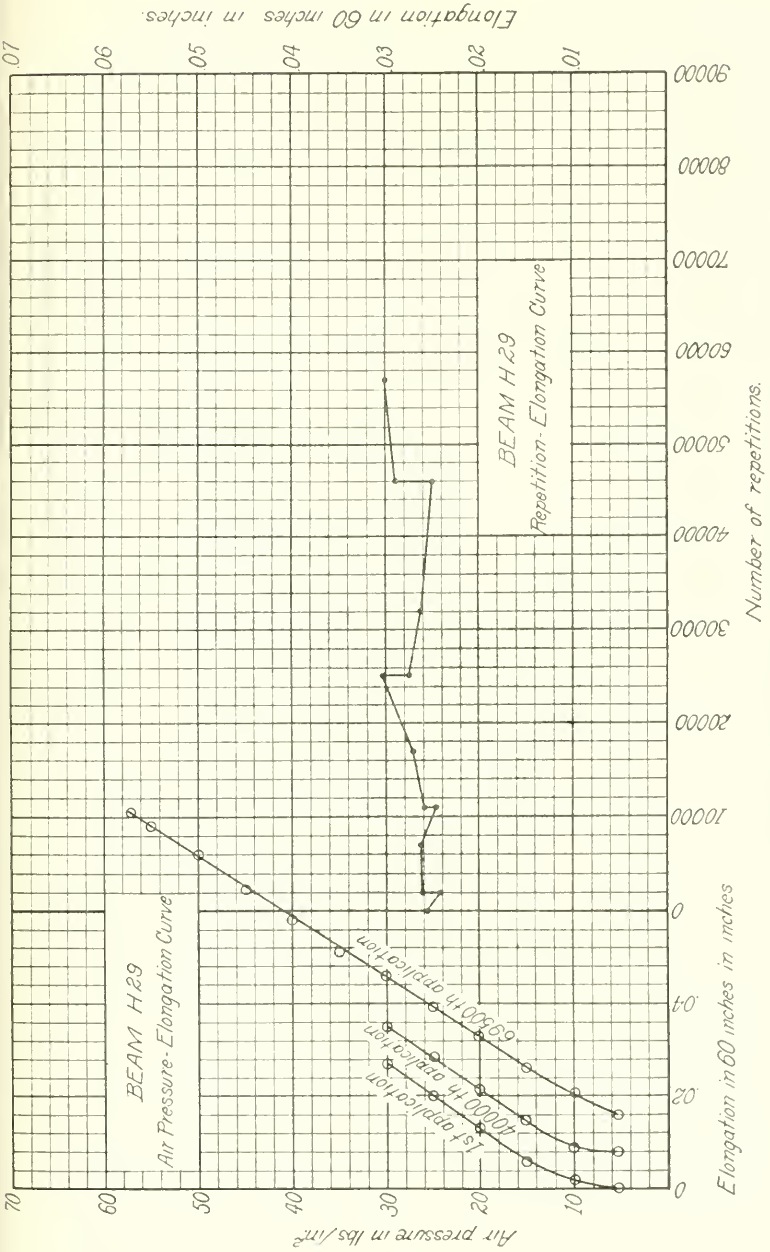


FIGURE 18.—BEAM H 29—RUSTED ROUND ROD—REPEATED TEST.

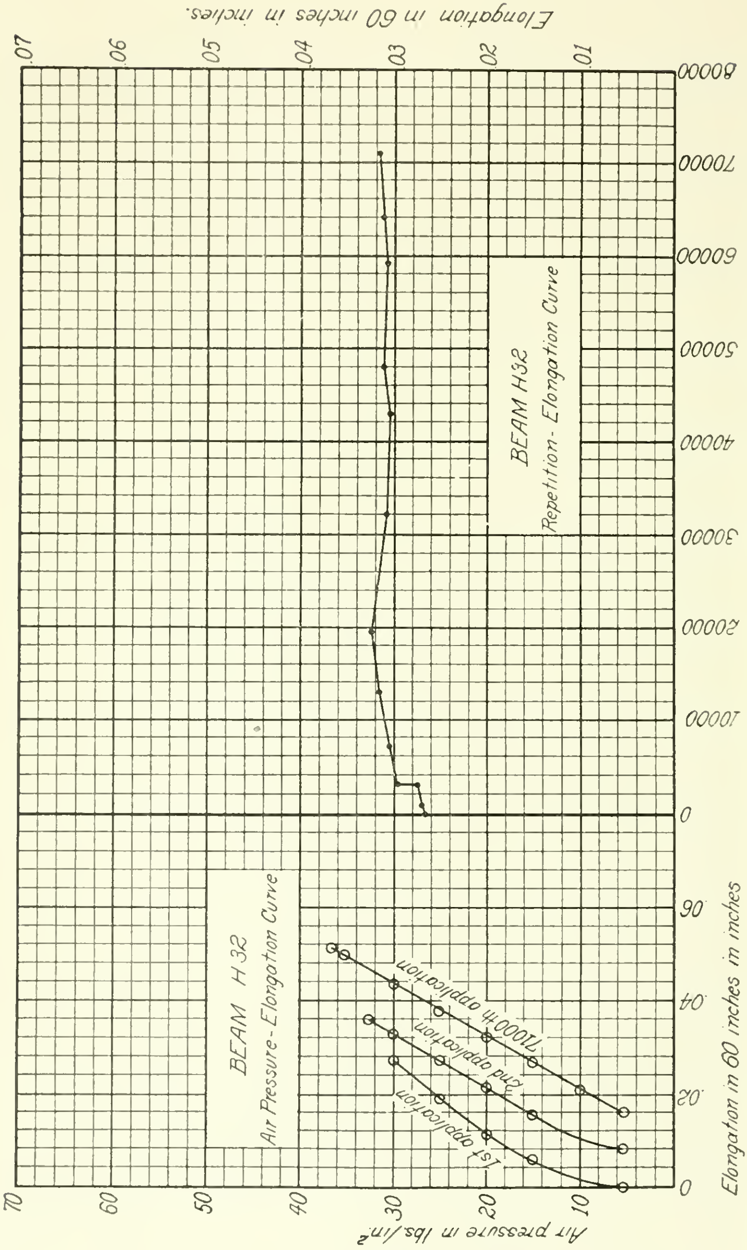


FIGURE 19.—BEAM H32—RUSTED ROUND ROD—REPEATED TEST.

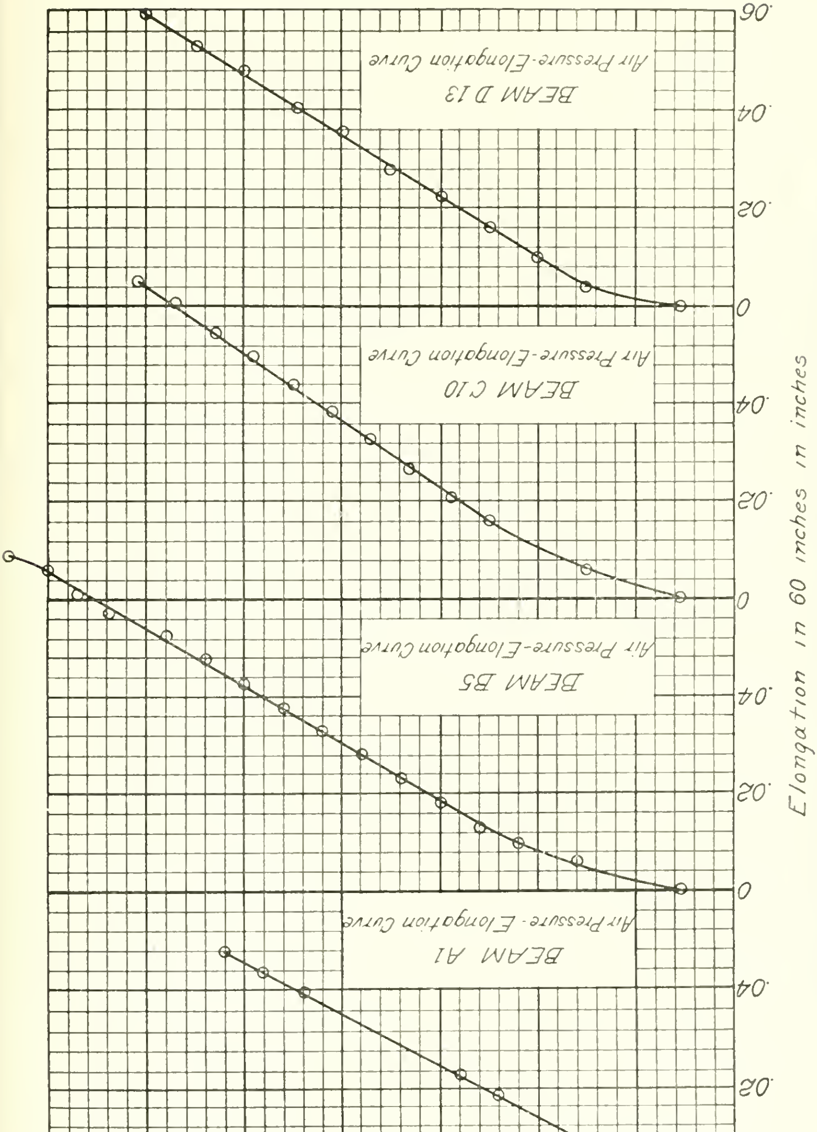


FIGURE 20.—BEAMS A1, B5, C10, AND D13—CORRUGATED BARS—STATIC TESTS.

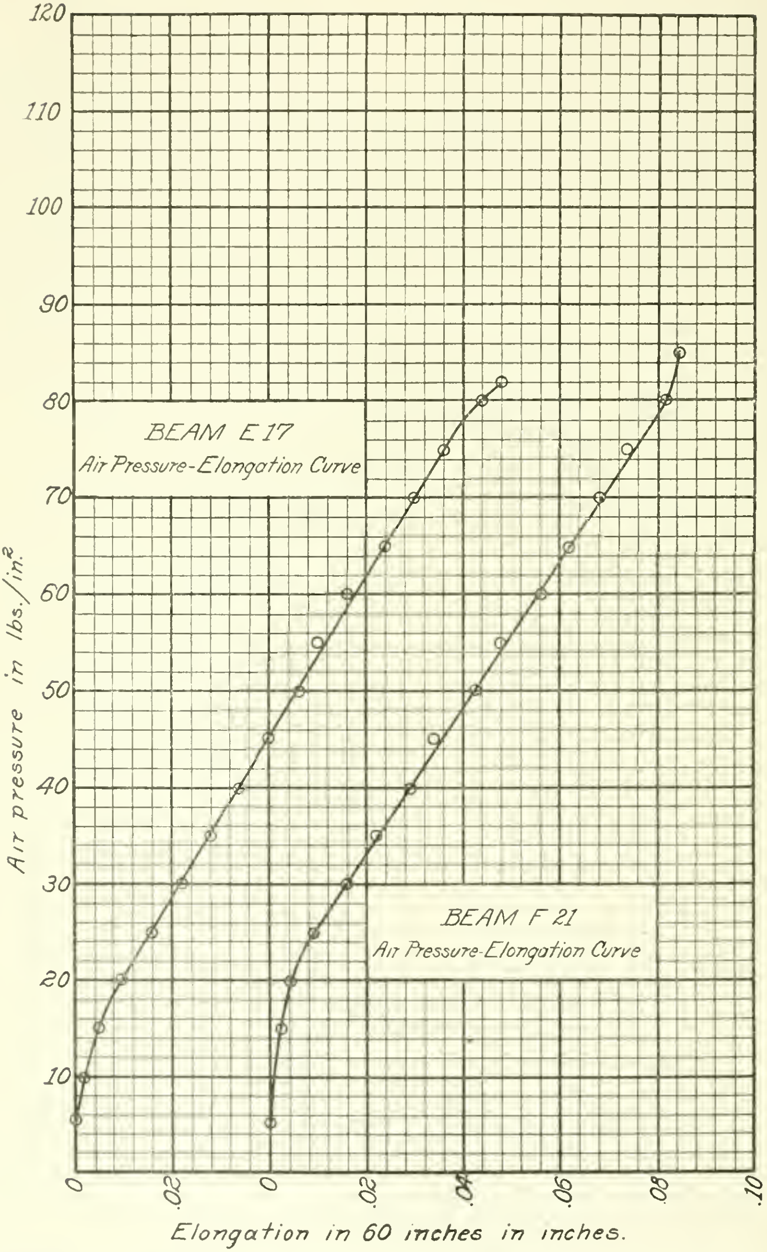


FIGURE 21.—BEAMS E 17 AND F 21—CORRUGATED BARS—STATIC TESTS.

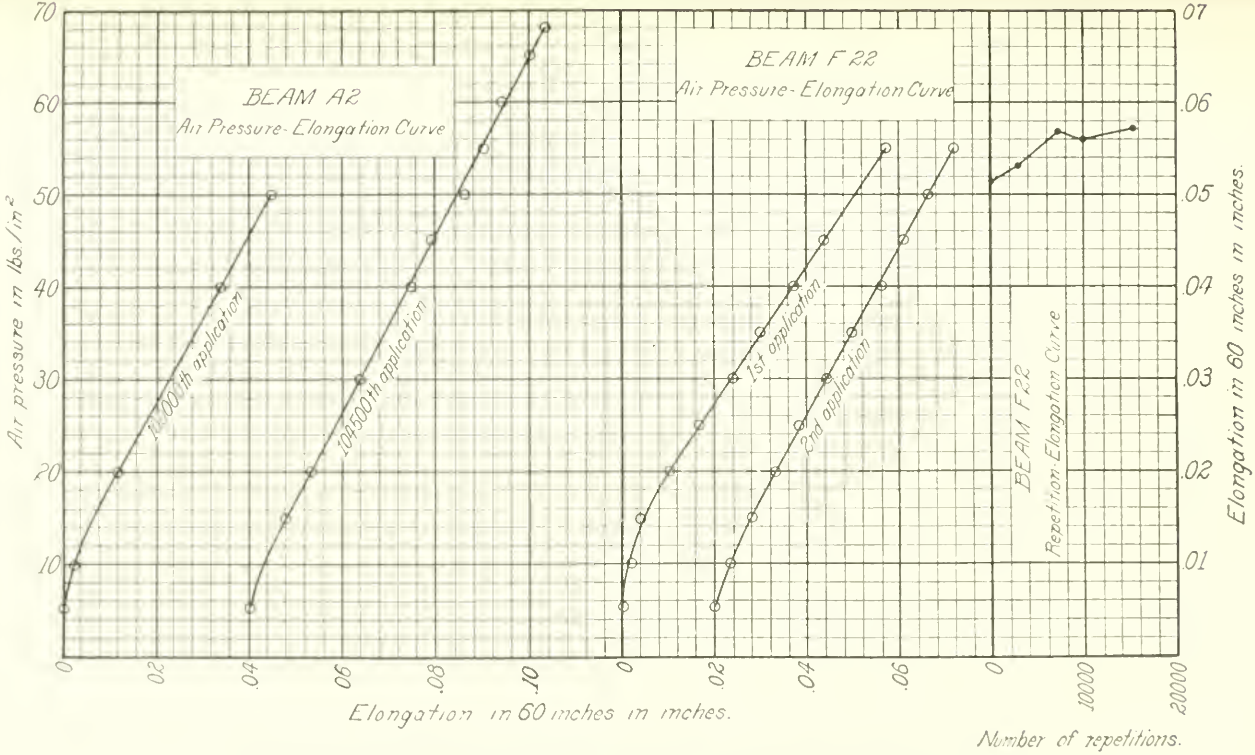


FIGURE 22.—BEAMS A2 AND F22—CORRUGATED BARS—REPEATED TESTS.

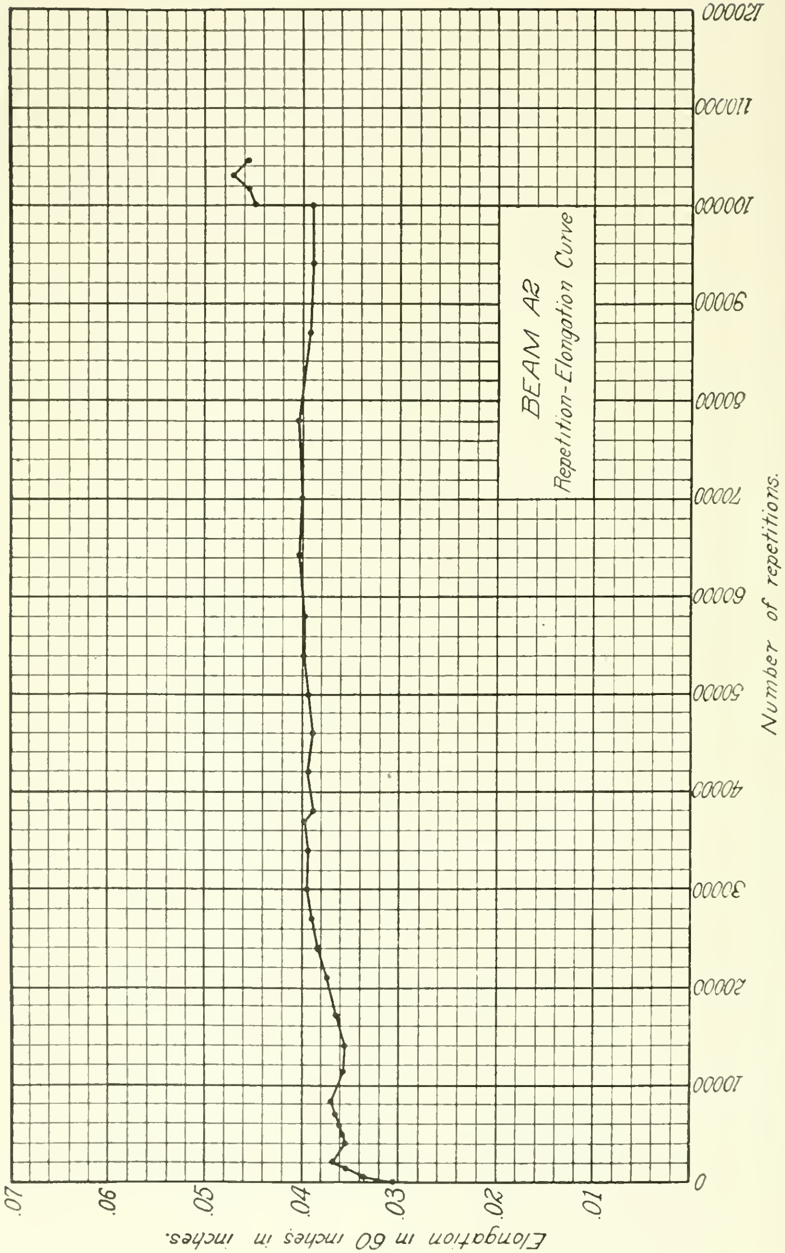


FIGURE 23.—BEAM A 2—CORRUGATED BAR—REPEATED TEST.

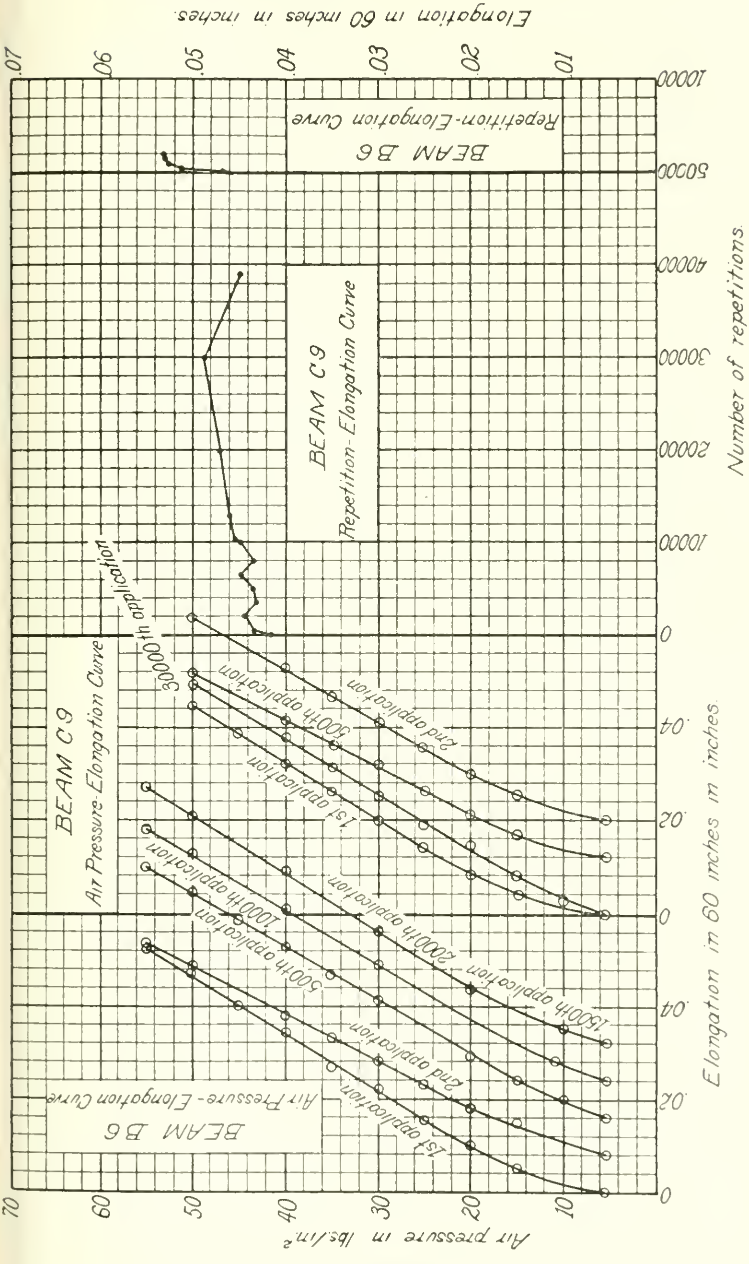


FIGURE 24.—BEAMS B6 AND C9—CORRUGATED BARS—REPEATED TESTS.

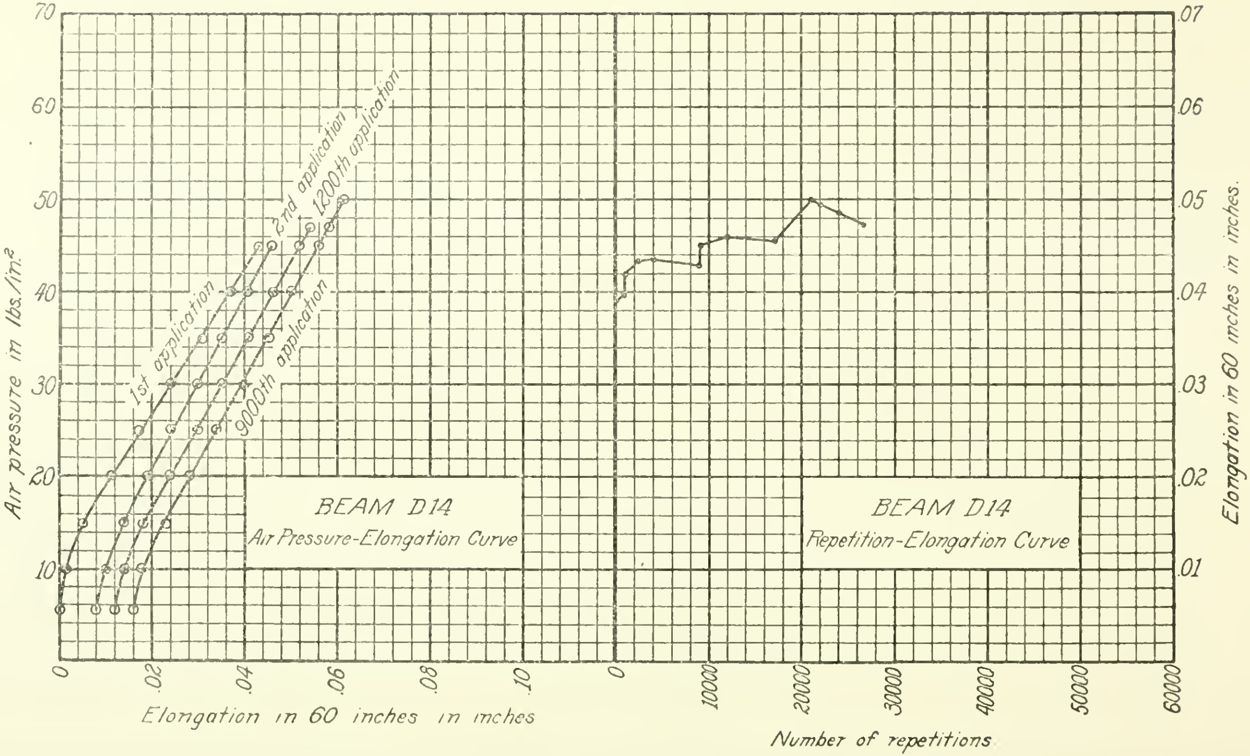


FIGURE 25.—BEAM D 14.—CORRUGATED BAR—REPEATED TEST.

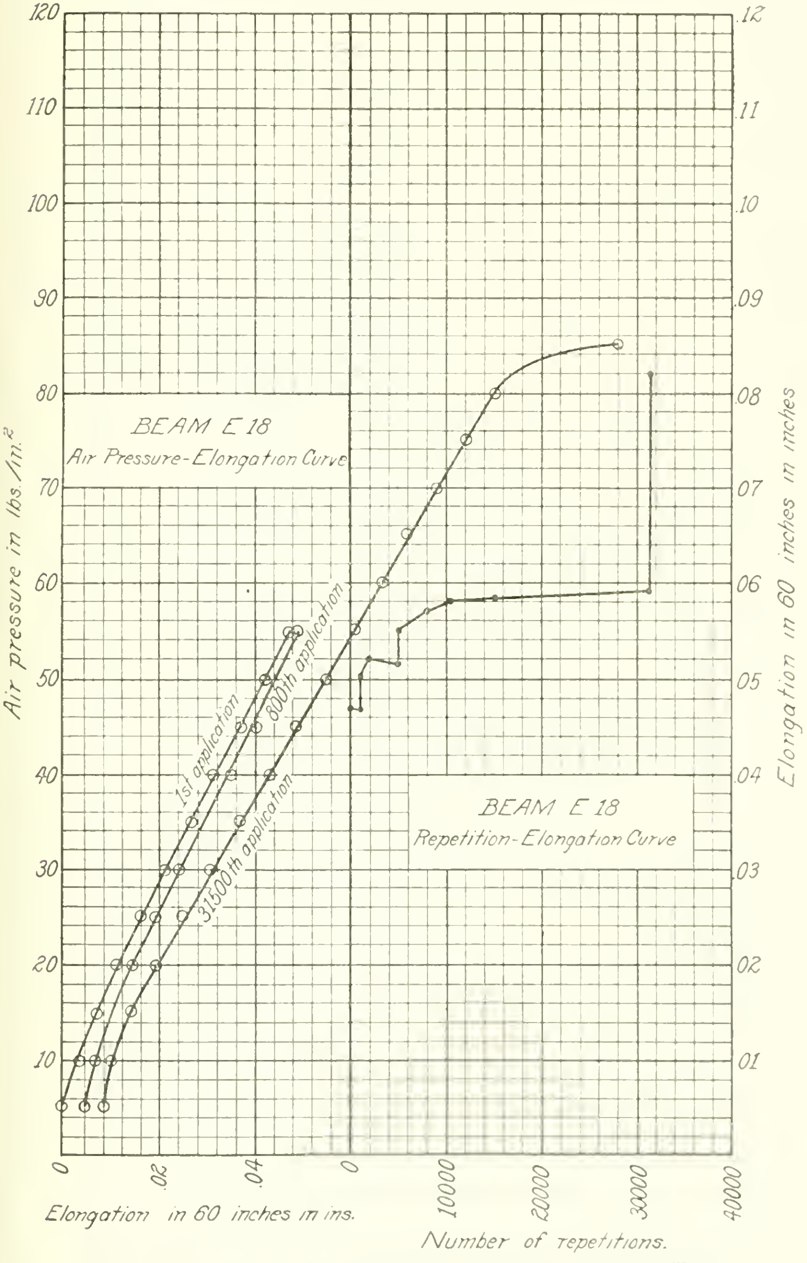


FIGURE 26.—BEAM E18—CORRUGATED BAR—REPEATED TEST.

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THE RELATIONS OF EXPERIMENTAL RESULTS TO THE THEORY OF THE TANGENTIAL WATER WHEEL

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FOREWORD

Hydraulics, while based on the exact sciences of hydrostatics and dynamics, is largely empirical. While its laws are founded on theory, the results are so limited and modified by the physical conditions under which they obtain, and our knowledge of the factors which enter into the problem and the extent of their influence is so limited, that the expression for these laws must be modified by observation and experience and cannot be founded solely on theory. The science of hydraulics has been established by theoretical investigation, substantiated by experimental research, but the range of such research is not satisfactory or complete. In order to fairly well cover the field of experimentation on which this science must be based. it is necessary that such experimental work be sufficiently broad to cover all conditions which might give rise to variation in the application of the principles which have been established on limited experimental data. Those who have had to do with such experimental work recognize the large expense of both time and money necessary for a careful and complete investigation of even one elementary branch of this science.

In the hydraulic laboratory of the University of Wisconsin various hydraulic investigations have been and are being made by skilled experimenters with the use of the most accurate instruments and methods in order to determine with the greatest practicable accuracy the fundamental relations that exist in the various subjects under investigation. The expense in time and apparatus is found to be so great that such investigations must of necessity be limited in extent. A considerable variety of hydraulic machines and apparatus is available at the laboratory for experimental research work, and a considerable number of students annually elect certain lines of hydraulic investigation for thesis subjects. Such investigations are carried on under the supervision of members of the faculty of the department of hydraulic and sanitary engineering, and an effort is made to see that the methods used are substantially correct and that the work done is reasonably accurate. Sufficient supervision cannot be given to this work to assure the highest degree of accuracy, and in many cases the results obtained are not satisfactory and are of little value toward establishing hydraulic principles or illustrating principles already tentatively established but not fully demonstrated by experimental proof. On the other hand, much of this experimental work, while not of the highest degree of accuracy, still illustrates and confirms established principles which need, however, for their full confirmation more experimental determinations than are commonly available.

The practicing engineer has little time or opportunity for experimental work. His calculations, estimates, and designs must be frequently based on principles which, while he is obliged to accept them in their common form, he yet feels are not as well established by practical demonstration as he might desire. In many cases practical proof of their application is difficult of access or entirely inaccessible. In the records of the laboratories of our colleges and universities is much data of this kind, which, if carefully selected and discussed, would be of very great value and aid to the engineering profession. Granting that such experimental work is liable to errors, the errors involved are commonly not of as great magnitude as margins for safety which the engineer must allow in his estimate on account of lack of data on which such estimates are based. In a broad subject like hydraulics, quantity of data is almost as essential as quality, provided the quantity can be obtained without too great a deterioration in the quality. It is therefore the belief of the writer that much of the best student work, in which the errors of experiment are known to be comparatively small, can be made available to the advantage of the hydraulic engineer and should be made accessible with due consideration of its character and the possible limits in its accuracy.

Many of the errors developed in such work are in themselves not without their value, for these very errors are frequently the result of conditions which, if repeated in actual installations, would and do have a similar effect on the actual results obtained.

It is also to be remarked that the errors in such experimental work are frequently not so large or so important as similar errors which creep into practical field observations made by practicing engineers who have not the time, the apparatus, or the experience to successfully perform experimental work with the facility with which it can be accomplished in a university laboratory. In his own practice as a hydraulic engineer, prior to his connection with the University of Wisconsin, the writer has recognized the importance of more data on a large variety of hydraulic subjects. In his work at the university it has been his endeavor to suggest to students, desiring to take up hydraulic research work, a line of subjects for such investigations on which he knew that further information was desirable. He feels, therefore, that the results of such investigations cannot be without value to the engineering profession, and proposes to offer, from time to time, a discussion of such experiments as will best illustrate important hydraulic principles.

THE RELATIONS OF EXPERIMENTAL RESULTS TO THE THEORY OF THE TANGENTIAL WATER WHEEL

INTRODUCTION

While a great many experiments with, or tests of, reaction water wheels have been made at the Holyoke Testing Flume, and a few trials of such wheels have been made in and under their operating conditions, yet comparatively few tests have been made of impulse and tangential wheels, and of such as have been made and published, few, if any, have been made in sufficient detail to form the basis of a fairly complete discussion of the various theoretical relations and the relation of theory to practice in the actual operation of such wheels. The principles underlying the design of these wheels have been quite thoroughly discussed, but the theoretical results are largely limited by practical conditions, and a general discussion of these principles together with a practical application, as demonstrated by a fairly complete series of tests on a wheel of this character, is believed to be of considerable interest to the engineering public.

The basis of this discussion is a series of experiments made on a 12″ Doble tangential wheel by Messrs. H. J. Hunt and F. M. Johnson at the hydraulic laboratory of the University of Wisconsin in the years 1905–06. Messrs. Hunt and Johnson, then senior students in the engineering department of the University of Wisconsin, made these experiments as the basis of a thesis for their baccalaureate degree.

The results of these experiments were only partly and briefly discussed in the thesis and are here considered in greater detail.

Detailed tabulated results of these tests are published in the appendix to this bulletin, and all of the results are shown in the diagrams accompanying the discussion. These tests are 620 in number and were made with much care, and, while the actual results of the same show a considerable variation from the theoretical conditions, they may, as a general proposition, be regarded as no greater departure than would ordinarily be found in actual practice. It must be remembered, however, that the wheel is a small one and that the element of friction in bearings, etc., is probably considerably greater than in the case of most larger machines under operating conditions.

In the preparation of this discussion, the writer has been materially assisted in some of the mathematical discussions by Mr. L. F. Harza, and by Mr. W. J. Wadsworth in the calculations and in the preparation of the diagrams.

CONDITIONS OF THE TEST

The wheel tested was a 12 inch tangential wheel, manufactured by the Abner Doble Company of San Francisco. The wheel was equipped with a Doble Needle Nozzle, and was furnished with water from the pressure tank of the University Water Works System. The hand wheel of the needle nozzle was provided with a pointer and circular scale so that the position of the needle during any test could be accurately recorded and reproduced, if it was found desirable to repeat any experiment.

The possible error in determining head by reading the gage, also the possible fluctuations in head due to other uses of water in the laboratory, and any possible errors in resetting the valve, due to lost motion, etc., although probably small, were the same quantitatively for all nozzle openings; and the percentage of possible error therefore was much greater at smaller openings and at lower heads. It will be observed from the experiments that the variations in discharge at the smaller openings and lower heads are among the largest errors of this series of tests.

The discharge from the wheel was received in a large galvanized iron tank, and the quantity of water discharged during any experiment was determined by weight. Water was furnished through a supply pipe under about 80 lbs. pressure, and the pressure at which water was delivered to the nozzle was varied and controlled by a gate valve in the pipe some distance away from the wheel. The head acting on the turbine was determined by a Bourbon pressure gage, carefully calibrated, and connected to the supply pipe a short distance from the nozzle entrance by four one-quarter inch pipes, ninety degrees apart. The arrangement of the wheel, friction brake, etc., is perhaps better shown and can be better understood by reference to Figs. 1, 2, and 3. The brake was of the ordinary Prony type gripping a small pulley 7.75 inches in diameter and with a 4 inch face, so arranged that cold water could be supplied to its inner circumference to reduce the heat due to the application of the brake and permit of more steady and uniform operation. The buckets of this wheel are of the well known Doble ellipsoidal type, made of gun metal carefully ground and smoothly polished upon the inner or hydraulic surface. (See Fig. 4.) Fig. 5 is a section through the needle nozzle. The opening or area, a, of the nozzle is increased or reduced by withdrawing or advancing the needle. b. and the resulting jet of water is under all conditions of discharge a well defined solid stream of water. practically free from all currents. eddies, or other disturbances, as shown by the photograph. Fig. 6. The wheel is carefully balanced. and the shaft runs in ring oiling bearings.

The time of each experiment was measured by means of a stop watch and the revolutions were determined by a revolution counter. A slotted pin was screwed into a hole drilled in the end of the shaft, and the stem of the revolution counter fitted into this slot. so that there was no lost motion between the shaft and the counter.

The head of water acting on the wheel was the head shown by the gage, reduced from pounds to feet by multiplying by 2.307. To this was added the height of the gage above the center line of the jet which was 1.51 feet, and the velocity head in the pipe, $h = \frac{v^2}{2g}$. which at the maximum was only .8 feet.

No determinations were made of the actual velocity of the water from the jet or of the efficiency of the nozzle, independently of the machine itself. All tests made, therefore, included nozzle losses. There was also included a small amount of un-

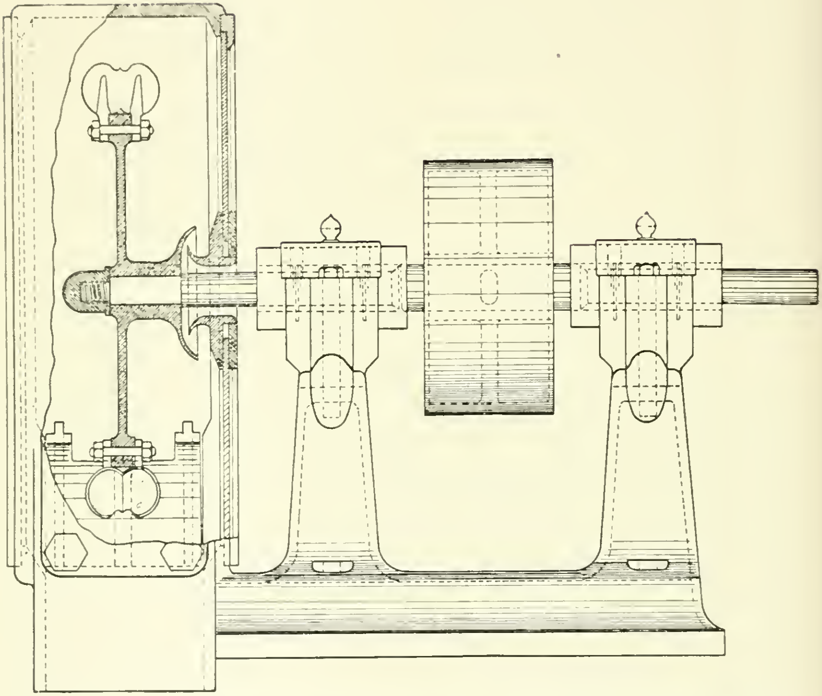


FIGURE 1.—ELEVATION AND PARTIAL SECTION THROUGH DOBLE WHEEL.

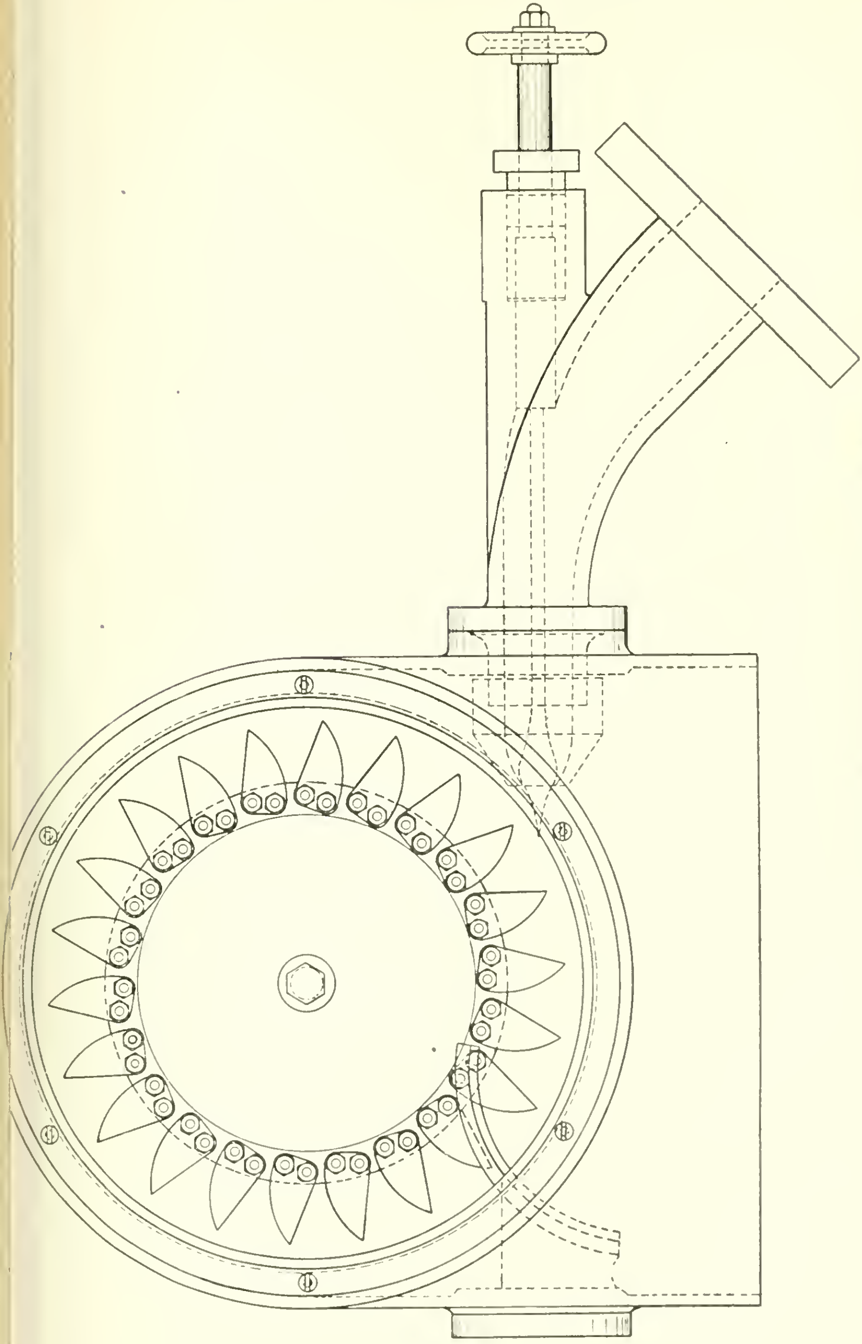


Figure 2.—Side Elevation of Doble Wheel.

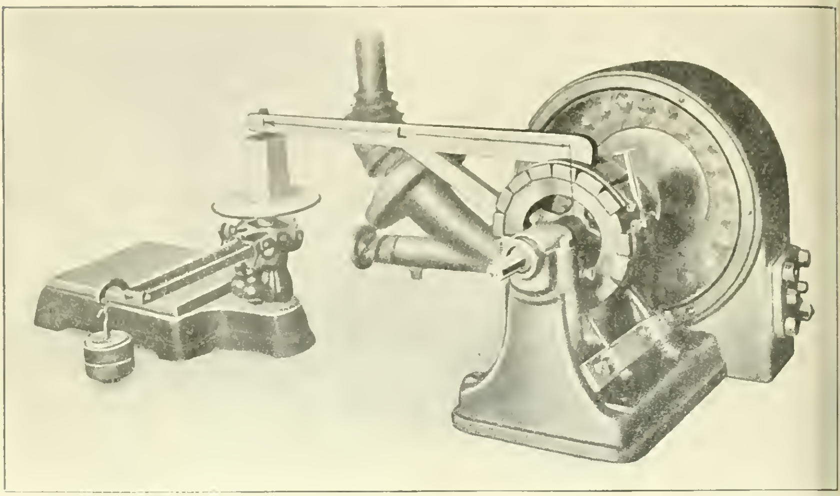


Figure 3.—Doble Tangential Wheel Arranged for Testing.

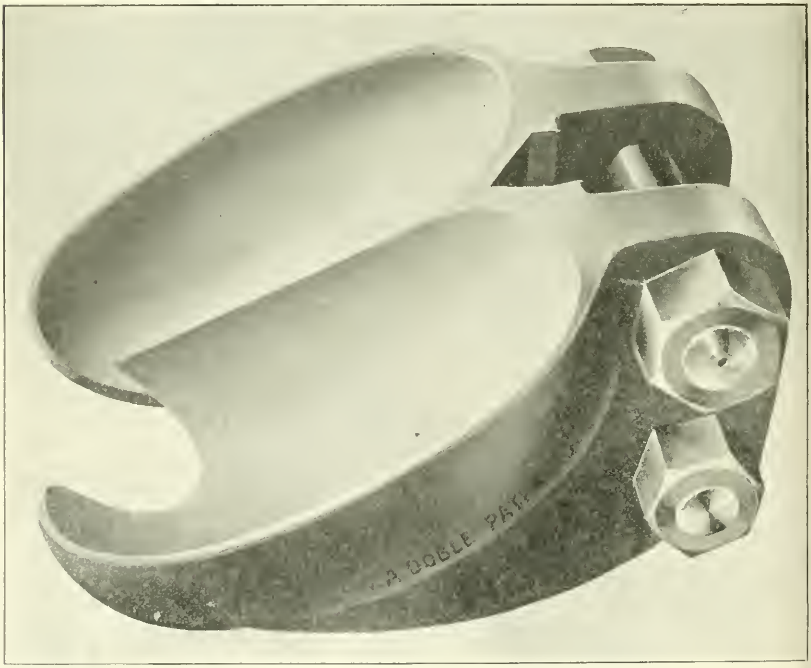


Figure 4.—Doble Ellipsoidal Bucket.

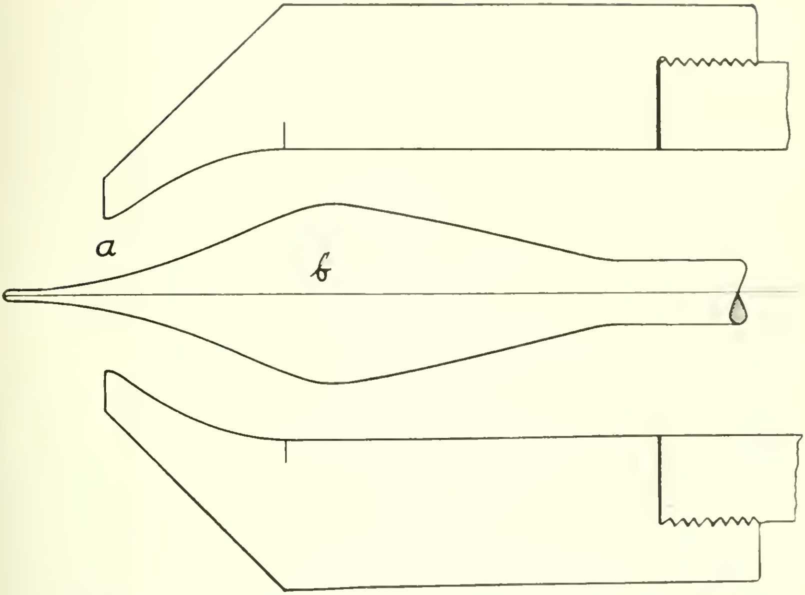


FIGURE 5.—SECTION THROUGH NEEDLE NOZZLE OF DOBLE TANGENTIAL WHEEL.

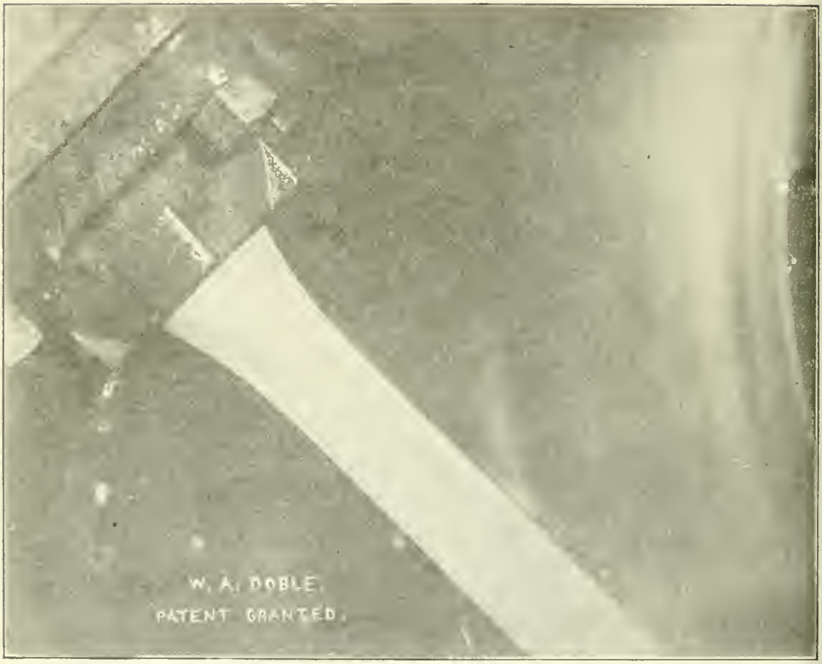


FIGURE 6.—JET OF WATER ISSUING FROM THE DOBLE TANGENTIAL REGULATING NOZZLE.

determined loss due to the friction in the pipe and elbow, leading from the pressure gage to the nozzle connection, and possibly a small loss due to cross currents and eddies set up by the elbows in the pipe leading to the nozzle. Those undetermined losses could not have extended a small fraction of one per cent of the total energy.

NOZZLE DISCHARGE

The wheel and nozzle of the tangential wheel (see Fig. 2) are so arranged that the jet of water leaves the nozzle entirely free and unimpeded and encounters the bucket after passing some distance from the nozzle. In consequence the nozzle discharges freely, and the discharge is not modified by the relative motion of the wheel as may be the case in other types of turbines.

The theoretical velocity of water, v, in feet per second, under a fixed head, h, through an opening or short tube of area, a, where the shape and area of the opening or tube are constant is

$$v = \sqrt{2gh} \tag{1}$$

The discharge in cubic feet per second, q, through such an opening is given by the equation

$$q = cva = ca\sqrt{2gh} \tag{2}$$

In this equation c is a coefficient depending on the character of the opening and is nearly constant for each fixed opening or condition of the nozzle. For each fixed opening, the values of c, a, and $\sqrt{2g}$ are nearly constant; their product, $ca\sqrt{2g}$, is equal to the discharge of the orifice under one foot head. Therefore, for each set of experiments under varying heads but with a constant opening of the nozzle, the calculated value of $ca\sqrt{2g}$ should be identical except as modified by experimental errors.

The experiments which are here considered were made under six conditions of nozzle opening. To entirely open the nozzle required $10\frac{7}{8}$ turns of the hand wheel. The experiments were made with the nozzle opened by two, three, four, six, eight, and ten and seven-eighths turns. Table I shows: 1. The head under which the experiments were made; 2. The discharge of the nozzle under the conditions of opening and the given heads; 3. The percentage of the discharge under the condition of opening to the discharge at the same head with the nozzle wide open; 4. The percentage of variation of each experiment, from the average percentage of all the experiments with a given opening; 5. The calculated discharge at one foot head, based on each experiment; 6. The percentage of the calculated discharge, under one ft. head, to the mean of the calculated discharge at full gate, under one ft. head, viz., .02756.

The extent and character of the errors in discharge due to the fluctuating head will be seen by reference to Column 5, and the magnitude of the variation is indicated by a comparison of the percentage in Column 4. The limits of the experimental errors in the entire set of experiments are more readily shown by reference to Fig. 7, in which are platted the calculated discharges under one foot head for the experiments given in Table I.

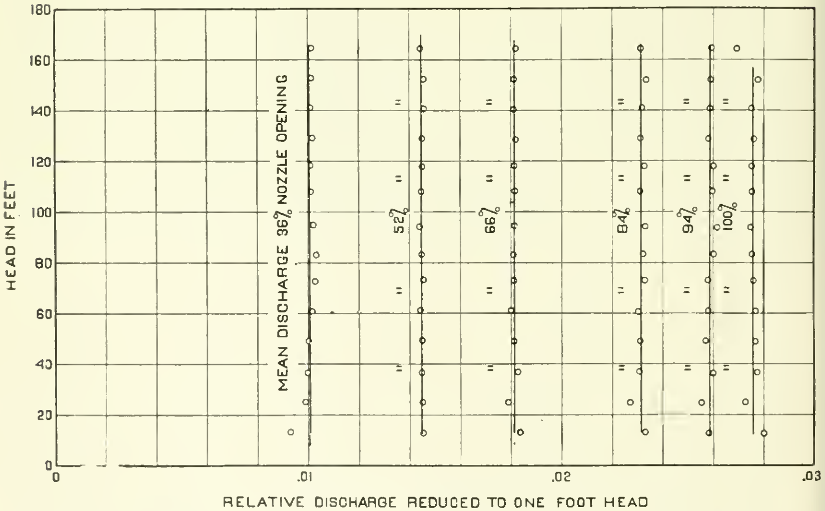


FIGURE 7.—MEASURED DISCHARGE OF NOZZLE, REDUCED TO CALCULATED DISCHARGE AT ONE FOOT HEAD.

TABLE I.

ACTUAL AND RELATIVE DISCHARGE OF NEEDLE NOZZLE OF DOBLE TANGENTIAL WHEEL.

(Nozzle open 2 turns)

Head.	Discharge in Sec. Ft.	Per cent of Full Discharge (Same head).	Per cent variation From Average.	Calculated Discharge 1 Ft. Head.	Per cent of Mean Discharge at Full Gate.
13.3	.034	33.3	—8.01	.00931	33.8
24.9	.049	34.1	—5.80	.00984	35.7
36.4	.060	35.9	—0.829	.00995	36.1
49.3	.070	36.1	—0.276	.00998	36.25
60.8	.079	36.6	+1.105	.01015	36.8
72.4	.087	37.0	+2.21	.01023	37.1
83.5	.093	37.1	+2.485	.01030	37.4
95.0	.099	37.0	+2.21	.01020	37.
108.0	.105	36.7	+1.38	.01010	36.7
118.4	.110	36.8	+1.66	.01010	36.7
129.7	.116	37.0	+2.21	.01020	37.
141.5	.120	35.8	—1.105	.01010	36.7
153.1	.125	36.5	+0.829	.01012	36.7
164.6	.130	36.8	+1.66	.01012	36.7
Mean..................		36.2		.01005	36.68

Nozzle open 3 turns.

13.3	.053	52.0	—0.76	.01452	52.65
24.9	.072	53.0	—1.14	.01445	52.4
36.4	.087	52.1	—0.57	.01445	52.4
49.3	.102	52.5	+0.19	.01445	52.4
60.8	.112	51.9	—0.95	.01440	52.22
72.4	.123	52.4	0.00	.01450	52.58
83.7	.132	52.5	+0.19	.01445	52.4
95.0	.140	52.2	0.38	.01439	52.2
108.0	.150	52.4	0.00	.01441	52.25
118.4	.158	52.8	+0.76	.01451	52.6
129.7	.165	52.6	+0.38	.01450	52.58
141.5	.173	52.9	+0.95	.01457	52.8
153.1	.180	52.5	+0.19	.01458	52.82
164.6	.185	52.3	—0.19	.01441	52.25
Mean..................		52.4	....	.01447	52.4

Nozzle open 4 turns.

Head.	Discharge in Sec. Ft.	Per cent of Full Discharge (Same head).	Per cent variation From Average.	Calculated Discharge 1 Ft. Head.	Per cent of Mean Discharge at Full Gate.
13.3	.067	66.0	+0.61	.01837	66.6
24.9	.089	65.5	—0.15	.01785	64.75
36.4	.110	66.0	+0.61	.01827	66.22
49.3	.127	05.5	—0.15	.01811	65.7
60.6	.140	64.9	—1.07	.01799	65.2
72.4	.154	65.5	—0.15	.01812	65.73
83.7	.165	65.6	0.00	.01808	65.58
95.0	.176	65.6	0.00	.01808	65.58
108.0	.189	66.0	+0.61	.01819	65.98
118.4	.197	65.9	+0.46	.01810	65.65
129.7	.207	65.9	+0.46	.01820	66.02
141.5	.25	65.8	+0.30	.01810	65.65
153.1	.224	65.4	—0.30	.01813	65.75
164.6	.233	66.7	+1.67	.01818	65.95
Mean..................		65.6	....	.01813	65.6

Nozzle open 6 turns.

13.3	.085	83.2	— .598	.02330	84.5
24.9	.113	83.0	— .836	.02267	82.2
36.4	.139	83.2	— .598	.02305	83.6
49.3	.162	83.6	— .119	.02310	83.8
60.6	.179	82.9	— .955	.02300	83.4
72.4	.198	84.1	+ .478	.02330	84.5
83.7	.212	84.1	+ .478	.02320	84.1
95.0	.229	84.4	+ .836	.02330	84.5
108.0	.240	83.9	+ .239	.02306	83.7
118.4	.253	84.6	+1.075	.02325	84.3
129.7	.263	83.9	+ .239	.02310	83.8
141.5	.275	84.1	+ .478	.02315	83.95
153.1	.283	84.0	+ .358	.02330	84.5
164.6	.296	83.6	— .119	.02305	83.61
Mean..................		83.7	....	.02313	83.6

Nozzle open 8 turns.

Head.	Discharge in Sec. Ft.	Per cent of Full Discharge (Same head).	Per cent variation From Average.	Calculated Discharge 1 Ft. Head.	Per cent of Mean Discharge at Full Gate.
13.3	.094	92.1	—1.6	.02580	93.6
24.9	.127	93.4	— .214	.02550	92.5
36.4	.157	94.1	+ .534	.02600	94.3
49.3	.180	92.9	— .748	.02570	93.2
60.8	.201	93.1	— .534	.02580	93.6
72.4	.219	93.1	— .534	.02580	93.6
85.7	.237	94.1	+ .534	.02600	94.3
95.0	.251	94.6	+1.069	.02610	94.7
108.0	.270	94.4	+ .855	.02600	94.3
118.4	.282	94.1	+ .534	.02600	94.3
129.7	.294	93.5	— .107	.02580	93.6
141.5	.307	94.0	+ .427	.02582	93.7
153.1	.320	93.1	— .531	.02590	93.9
164.6	.332	93.9	+ .320	.02590	93.9
177.4	.345	....		.02590	93.9
Mean..................		93.6	....	.02587	93.8

Nozzle fully open (open 10⅝ turns).

Head.	Discharge in Sec. Ft.	Per cent of Full Discharge (Same head).	Per cent variation From Average.	Calculated Discharge 1 Ft. Head.	Per cent of Mean Discharge at Full Gate.
13.3	.102	100		.02800	101.6
24.9	.136	100		.02725	98.9
36.4	.167	100		.02770	100.5
49.3	.194	100		.02765	100.3
60.8	.216	100		.02770	100.5
72.4	.235	100		.02760	100.2
83.7	.251	100		.02759	100.1
95.0	.268	100		.02751	99.85
108.0	.286	100		.02755	100.0
118.4	.299	100		.02748	99.7
129.7	.314	100		.02761	100.2
141.5	.327	100		.02750	99.8
153.1	.343	100		.02775	100.7
164.6	.351	100		.02690	97.6
Mean.		...	....	.02756	100.0

THEORETICAL CONDITIONS

ENERGY OF JET

The jet of water spouting from the nozzle of the wheel will acquire a velocity, v, due to the head, h, (see Equation 1) and will possess energy in foot pounds per second, E, due to velocity, v, and weight of water discharged per second ($W = qw$), as follows:

$$E_3 = \frac{Wv^2}{2g} = \frac{qwv^2}{2g}. \tag{3}$$

FORCE PRODUCING JET

The energy of the jet leaving the orifice is the product of a force, F′, which, acting on the weight of water, qw, for one second, gives it the velocity, v. The space passed through by the force in one second in raising the velocity from o to v is

$$S = v_a t = \frac{v}{2} \tag{4}$$

and the work is therefore

$$F'S = \frac{F'v}{2} \tag{5}$$

which is also an expression for the energy of the jet. Therefore we may write

$$\frac{F'v}{2} = \frac{qwv^2}{2g} \tag{6}$$

and therefore

$$F' = \frac{qwv}{g}. \tag{7}$$

PRESSURE OF AN IMPINGING JET

The force, F, will be exerted against any obstruction in its path, and its magnitude will depend on the momentum of the moving stream of water and is directly proportional to its velocity. It is also a function of the angle through which the jet is deflected. If friction be ignored the stream will be diverted without change in velocity and the force exerted in the original direction of the jet will be equal to the momentum of the original stream less the component, in the original direction, of the momentum of the diverted jet. (See Fig. 8.)

$$F = \frac{qwv}{g} - \frac{qwv}{g}\cos\alpha = \frac{qwv}{g}(1 - \cos\alpha). \tag{8}$$

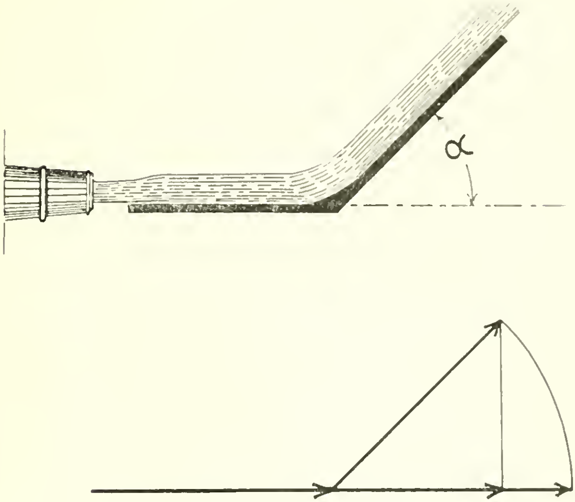


FIGURE 8. FORCE OF DIVERGING JET.

If the jet impinges against a flat surface (see Fig. 9), $\alpha = 90°$, $\cos\alpha = 0$, and

$$F = \frac{qwv}{g}. \tag{9}$$

If the jet is deflected 180° by means of a semi-circular bucket, $\cos 180° = -1$, and therefore (see Fig. 10)

$$F = 2\frac{qwv}{g}. \tag{10}$$

PRESSURE ON MOVING BUCKETS

Tangential wheels utilize the impulsive force of a jet impinging against buckets attached to their circumference and practically semi-circular in section.

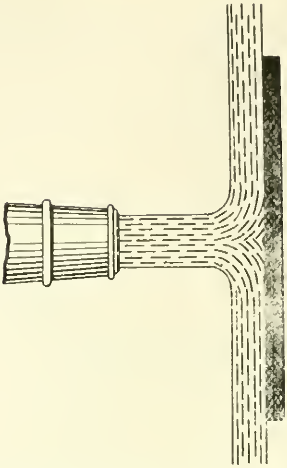


FIGURE 9.—JET DIVERGING 90°.

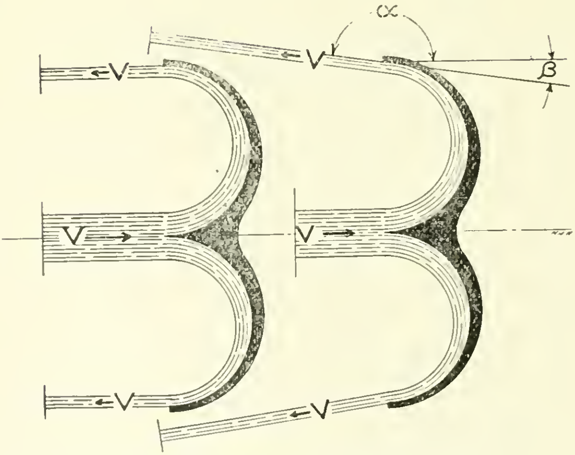


FIGURE 10.—JET DIVERGING 180°.

The bucket must move under the impulse in order to transform the energy of the impact, and the ratio of v′, the velocity of the center of the buckets, to the velocity, v, of the jet, is indicated by ϕ or,

$$\phi = \frac{v'}{v}. \tag{11}$$

The force, F, exerted on the moving bucket is dependent on the relative velocity, v_r, of the bucket and jet.

$$v_r = v - \phi v = (1 - \phi) v. \tag{12}$$

The relative weight of water that strikes a single bucket per second will also be less on account of the movement of the buckets. But as new buckets constantly intercept the path of the jet, the total amount of water effective is equal to the total discharge of the jet, hence from Equation 8

$$F = (1 - \cos \alpha) \frac{qwv}{g} (1 - \phi). \tag{13}$$

Most Efficient Speed

The energy expended on the buckets per second is equal to the force, F. times the distance, ϕv, through which it acts, i. e.

$$E_4 = (1 - \cos \alpha) (1 - \phi) \frac{qwv}{g} \phi v. \tag{14}$$

This is a maximum when $(1 - \phi)\ \phi$ is a maximum or when $\phi = 0.5$. Substituting $\phi = .5$ and $\alpha = 180°$ above, we then obtain:

$$E_4 = \frac{qwv^2}{2g} \tag{15}$$

or E_4 equals the entire energy of the jet. (See Equation 3.)

Another criterion for maximum efficiency is that the absolute velocity of the water in leaving the bucket should be minimum. When $\alpha = 180°$, the absolute velocity with which the water leaves the bucket is evidently the velocity relative to the bucket minus the velocity of the bucket, or

$$v_r = (1 - \phi) v - \phi v = v - 2\phi v, \tag{16}$$

from which, for maximum efficiency, $v - 2\phi v = o$ or $\phi = 0.5$.

It is also evident from Equation 14 that E_4 will equal zero whenever $\phi = 0$ or $\phi = 1$. In the first case the entire energy of the jet is expended in pressure against the bucket with no motion and consequently no power results. In the last case, the bucket moves as fast as the water and no pressure or power results.

Energy Lost in Discharge

In an impulse wheel it is not practicable to change the direction of the water through 180° as it would then interfere with the succeeding bucket. (See Fig. 10.) The angle α must hence be less than 180° and the absolute velocity of the water in leaving the buckets cannot be zero. The loss from this source is small as angle α may differ considerably from 180° without much effect on the bucket pressure, and hence on the efficiency.

For example, the ratio of actual bucket pressure for any angle α to maximum possible pressure, with $\alpha = 180°$, is

$$(17) \qquad \frac{(1 - \cos \alpha)\, qw\, (1 - \phi)\, (1 - \phi)\, v}{(1 - \cos 180°)\, qw\, (1 - \phi)\, (1 - \phi)\, v} = \frac{1 - \cos \alpha}{1 - \cos 180°}$$

$$= \frac{1 - \cos \alpha}{2} = \frac{1 + \cos \beta}{2}. \quad \text{(See Fig. 10.)}$$

If $\beta = 8°$, $\alpha = 172°$ and $\frac{1 - \cos \alpha}{2} = .995$, showing only ½ per cent. reduction. The effect on the efficiency is in the same ratio.

Graphical Illustration of Flow

Fig. 11 illustrates graphically the flow of water into and through the bucket of a tangential wheel at the most economical relative velocity. The bucket is double, each half being essentially semi-circular in section. v is the absolute velocity of the jet; v' is the absolute velocity of the bucket; v_r is the relative velocity of the jet in relation to the bucket: or $v_r = (1 - \phi)\, v$.

The bucket is moving in the direction BB′ and occupies successively the positions indicated by the vertical lines a, a_1, a_2, etc., in equal intervals of time. The water moves along the surface of the bucket with a uniform velocity, v_r, passing suc-

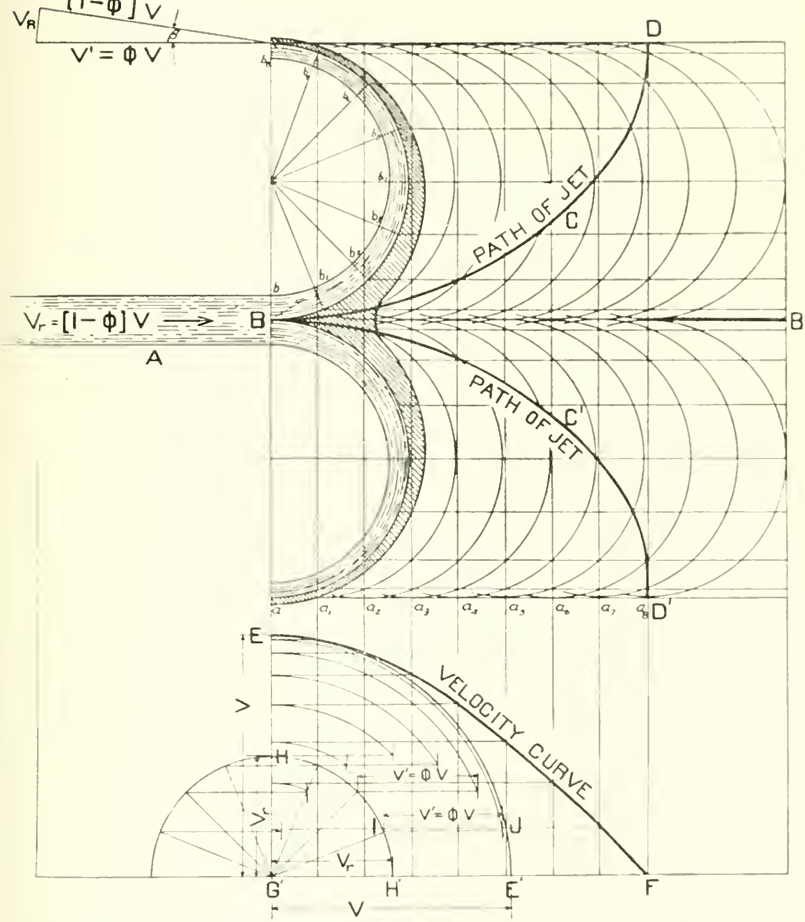


FIGURE 11.—GRAPHICAL ILLUSTRATION OF FLOW IN TANGENTIAL BUCKETS.

cessively through equal distances, indicated on the surface of the bucket by the lines b, b_1, b_2, etc., in equal intervals of time.

At each of these successive points, the jet has changed its direction and its absolute velocity. Its path through space is represented by the line BCD. The change in velocity is represented by the absolute velocity curve, EF, in which ordinates are the resultants obtained by applying the principle of triangle of velocities to corresponding velocities of the bucket and of the water relative to the bucket.

At the time of entering the bucket, the stream has the absolute velocity, v, represented by the length of the lines GE and GE′ in the lower diagram, while its velocity relative to the bucket is constant and equal to v_r, equal to the length of lines GH and GH′. For the most efficient speed, $v_r = \frac{v}{2}$.

At the end of the first interval of time, the jet has moved from the original point of contact with the bucket, b, to the position b_1. Its direction and velocity in the upper half of the bucket are represented by the radius GI in the lower velocity diagram. $v' = \phi v$, is constant both in magnitude and direction, and this is laid off in the lower diagram on the line IJ. The resultant of these two velocities is represented by the line GJ which is the absolute velocity of the water in space, and to indicate the velocity of the water at this instant is laid off for the purpose of the velocity diagram on the ordinate a_1, from the axis GF as 0 in the lower diagram. In the same manner each of the remaining points on the velocity curve EF is constructed.

The jet leaves the bucket as shown with a velocity, relative to the bucket, of $(1 - \phi)$ v. If this velocity is combined graphically with the velocity of the bucket, ϕv, the true absolute residual velocity, v_r, of the water will be obtained. The efficiency is evidently maximum when ϕ has a value which makes v_r a minimum. This condition can be shown to obtain when the triangle is isosceles or when

$$\phi v = (1 - \phi)\ v \text{ which gives}$$
$$\phi = 0.5$$

as obtained by two other methods.

EFFICIENCY

The efficiency of the tangential wheel is the ratio of the energy delivered by the wheel to the energy which is supplied to the wheel, but the term efficiency may have various significations, dependent on where the energy, resulting or applied, is measured.

If the applied energy is measured in the forebay, the energy available is expressed by

$$E_1 = qwh. \tag{18}$$

The energy just before entering the nozzle is

$$E_2 = qw(h - h'). \tag{19}$$

The energy of the jet is (see equation 3)

$$E_3 = \frac{qwv^2}{2g}$$

and the theoretical energy delivered to the bucket is (see equation 14)

$$E_4 = \frac{qw\phi\,(1 - \phi)\,(1 - \cos\alpha)\,v^2}{g}.$$

If E′ represents the foot pounds of work actually delivered by the wheel per second, then

(20) $\frac{E'}{E_1}$ = the efficiency of the entire installation, including headworks, pipe, jet, buckets, bearings, etc.

(21) $\frac{E'}{E_2}$ = the efficiency of the complete water wheel, including nozzle, buckets, bearings, etc.

(22) $\frac{E'}{E_3}$ = the efficiency of the wheel, including buckets and bearings only.

(23) $\frac{E'}{E_4}$ = the efficiency of wheel, including buckets and bearings, and taking speed of wheel into account.

EFFICIENCY OF BUCKETS

The theoretical pressure exerted on the buckets of practically circular cross section when at rest is (see equation 10)

$$F = \frac{2qwv}{g}.$$

In testing the wheel with the Prony brake, the actual force or pressure of the jet against the buckets when the wheel is stationary is measured by the pressure indicated on the scale, multiplied by the ratio of the length of brake arm to the wheel radius.

$$F_a = \frac{l}{r} L \qquad (24)$$

and the bucket efficiency is the ratio

$$e_b = \frac{F_a}{F}. \qquad (25)$$

Efficiencies at Rest

In the experiments in Table II, the wheel was held stationary by the brake. The wheel was not arranged so that the jet would strike the buckets squarely, but was taken in the position that it chanced to stop, as no single position could be considered as fairly representative.

In general these experiments show that the efficiency is higher as the quantity of water is reduced. In other words: the smaller the quantity of water, the more efficiently the jet acts on the bucket. This is also clearly demonstrated in the characteristic curves hereafter considered.

It should be noted also that the theoretical velocity of the water is used as the basis for calculation, so that the measurements made may be regarded as representing the combined efficiency of nozzle and buckets, windage and journal friction being practically eliminated in the stationary buckets.

From equation 13,

$$F = (1 - \cos \alpha) \frac{qwv}{g} (1 \quad \phi).$$

Assume a semi-circular bucket ($\cos \alpha = -1$). Then

$$F = \frac{2\,qwv}{g} (1 - \phi). \qquad (26)$$

TABLE II.

CALCULATED AND MEASURED PRESSURE OF JET ON STATIONARY BUCKETS UNDER VARIOUS HEADS AND WITH VARIOUS NOZZLE OPENINGS.

(2 turns of nozzle).

Head in feet.	Discharge in sec. ft.	Calculated pressure lbs.	Measured pressure lbs.	Per cent efficiency.	Per cent variation + or — from mean efficiency.
13.3	.034	3.85	3.875	100.50	+9.70
24.9	.049	7.60	7.625	100.20	+9.05
36.4	.060	11.25	10.625	94.50	+3.16
49.3	.070	15.25	14.125	92.60	+1.09
60.8	.079	19.20	17.375	90.50	—1.20
72.4	.087	23.00	20.375	88.50	—3.38
83.7	.093	26.42	23.625	89.50	—2.29
95.0	.099	30.00	26.625	89.00	—2.84
108.0	.105	34.00	30.125	88.50	—3.38
118.4	.110	37.20	33.375	89.60	—2.18
129.7	.116	41.10	36.375	88.40	—3.49
141.5	.120	44.50	39.875	89.60	—2.18
153.1	.125	48.00	43.125	90.00	—1.75
164.6	.130	52.30	46.625	89.40	—2.40
Mean				91.60	

3 turns of nozzle.

Head in feet.	Discharge in sec. ft.	Calculated pressure lbs.	Measured pressure lbs.	Per cent efficiency.	Per cent variation + or — from mean efficiency.
13.3	.053	6.00	5.875	98.00	+9.99
24.9	.072	11.15	10.375	93.00	+4.38
36.4	.087	16.30	14.625	89.70	+0.67
49.3	.102	22.30	19.125	85.80	—3.70
60.8	.112	27.20	23.625	87.00	—2.37
72.4	.123	32.50	28.125	86.60	—2.80
83.7	.132	37.50	33.375	89.00	—0.11
95.0	.140	42.50	37.675	88.60	—0.57
108.0	.150	48.40	42.625	88.40	—0.79
118.4	.158	53.10	46.875	88.10	—1.12
129.7	.165	58.40	51.625	88.60	—0.57
141.5	.173	64.90	56.875	86.00	—3.18
153.1	.180	69.30	61.875	89.20	+0.11
164.6	.185	74.30	66.125	89.10	0.00
Mean				89.10	

4 turns of nozzle.

Head in feet.	Discharge in sec. ft.	Calculated pressure lbs.	Measured pressure lbs.	Per cent efficiency.	Per cent variation + or − from mean efficiency.
13.3	.067	7.59	6.375	84.00	+0.60
24.9	.089	13.80	11.375	82.50	—1.19
36.4	.110	20.65	16.875	81.60	—2.28
49.3	.127	27.70	22.875	82.60	—1.08
60.8	.140	33.90	28.375	83.50	0.00
72.4	.154	40.70	33.625	82.70	—0.96
83.7	.165	47.00	38.875	82.70	—0.96
95.0	.176	53.30	44.375	83.10	—0.48
108.0	.189	61.00	49.875	81.60	—2.28
118.4	.197	66.20	56.125	85.00	+1.80
129.7	.207	73.30	61.375	83.60	+0.12
141.5	.215	79.60	67.875	85.10	+1.92
153.1	.224	86.10	73.125	85.00	+1.80
Mean				83.50	

6 turns of nozzle.

13.3	.085	9.61	8.125	84.50	+5.10
24.9	.113	17.50	14.575	83.30	+3.61
36.4	.139	26.10	21.125	81.00	+0.75
49.3	.162	35.40	26.625	75.40	—6.22
60.8	.179	43.50	35.375	81.30	+1.12
72.4	.195	51.60	41.875	81.00	+0.75
83.7	.212	60.20	48.125	80.00	—0.50
95.0	.227	68.90	54.875	79.60	—1.00
108.0	.240	77.50	61.625	79.60	—1.00
118.4	.253	85.00	68.625	80.80	+0.50
129.7	.263	93.10	73.875	79.20	—1.49
141.5	.275	105.50	81.625	77.50	—3.61
153.1	.288	111.00	88.125	79.50	—1.12
164.6	.296	119.00	95.500	80.20	—0.25
Mean..				80.40	....

8 turns of nozzle.

Head in feet.	Discharge in sec. ft.	Calculated pressure lbs.	Measured pressure lbs.	Per cent efficiency.	Per cent variation + or − from mean efficiency.
13.3	.094	11.62	8.50	73.00	....
24.9	.127	19.70	15.75	84.40	+2.00
36.4	.157	29.40	24.50	83.50	+0.91
49.3	.180	39.30	32.25	82.70	−0.60
60.8	.201	48.70	40.25	82.50	−0.31
72.4	.219	57.90	48.25	83.50	+0.91
83.7	.237	67.50	56.00	83.00	+0.31
95.0	.254	77.00	64.25	83.50	+0.91
108.0	.270	87.30	72.25	82.90	+0.18
118.4	.282	94.90	79.75	84.00	+1.50
129.7	.294	104.10	87.50	84.00	+1.50
141.5	.307	113.50	95.25	84.00	+1.50
153.1	.320	123.00	102.75	83.50	+0.31
164.6	.332	133.10	....	....	....
177.4	.345	142.50	....	....	....
Mean..				82.75	

10¾ turns of nozzle (full gate).

13.3	.102	11.55	9.50	82.20	+1.36
24.9	.136	21.00	16.25	77.40	−4.56
36.4	.167	31.40	25.25	80.50	−0.74
49.3	.194	42.40	34.50	81.50	+0.49
60.8	.216	52.40	41.75	80.00	−1.36
72.4	.235	62.00	49.75	80.30	−0.99
83.7	.251	71.40	57.25	80.30	−0.99
95.0	.268	81.20	66.25	81.60	+0.62
108.0	.286	92.50	74.25	80.40	−0.86
118.4	.299	101.00	83.25	82.50	+1.73
129.7	.314	111.20	90.75	82.40	+1.60
141.5	.327	121.00	99.50	82.20	+1.36
153.1	.343	132.00	107.50	81.50	+0.49
Mean..				81.10	

In order to account as nearly as possible for the losses under all conditions of operation, an analysis was made as follows:

It was first assumed that the two conditions which almost entirely control bucket efficiency are (1) quantity of water flowing over a single bucket in cubic feet per second; (2) velocity of the water over the surface of the bucket. The former is represented, when the bucket is in motion, by $(1 - \phi)$ q, and the latter by $(1 - \phi)\ \sqrt{2gh}$.

It can be assumed with reasonable accuracy that the running efficiency of the buckets is equal to the stationary efficiency when these two expressions are equal.

When the buckets are stationary, journal friction can be nearly eliminated from the measurements and windage is absent. The combined bucket and nozzle efficiency can therefore be determined for a stationary bucket and applied to a moving bucket. No method was available for distinguishing between bucket and nozzle losses, but the entire loss is considered as bucket loss since the nozzle loss is known to be very small. (See bulletin No. 6 of the Abner Doble Co.)

For a stationary bucket

$$(1 - \phi)\ q = q \text{ and}$$
$$(1 - \phi)\ \sqrt{2gh} = \sqrt{2gh}.$$

All experiments with fixed buckets were therefore platted in Fig. 12 with q as ordinates and $\sqrt{2gh}$ as abscissas, writing beside each platted point the efficiency obtained in that experiment.

It will be noted that for eight turns of the regulating needle, the efficiency was higher than on either side, tending to show two maximum points in the curve for any constant value of $(1 - \phi)\ \sqrt{2gh}$. This is, of course, incorrect relative to the other gate openings and probably due to a different position of the bucket which received the water during this set of readings.

Two sets of readings (Fm and Cg) were then analyzed to determine the effect of windage and journal friction. The points were platted in Fig. 12 with $(1 - \phi)$ q and $(1 - \phi)\ \sqrt{2gh}$ as arguments and the efficiency of the buckets then estimated from the nearby points as determined by the fixed buckets.

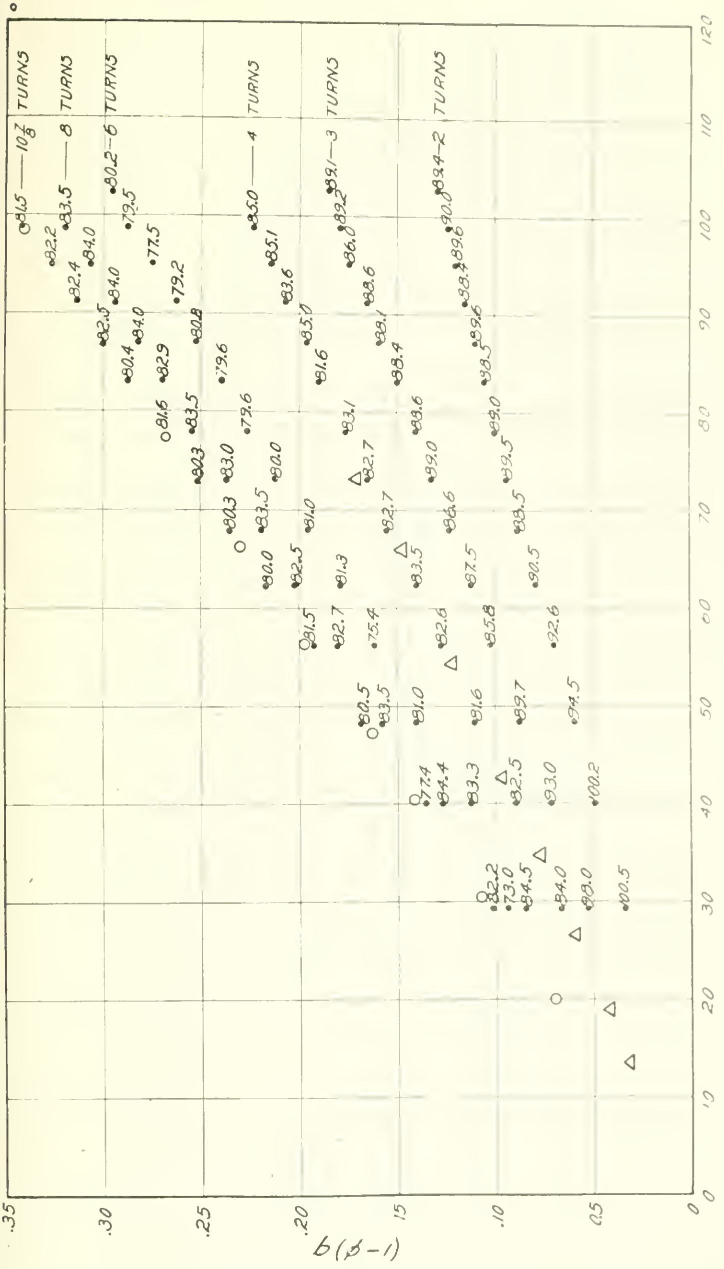


FIGURE 12.—EFFICIENCIES OF BUCKETS UNDER VARIATION OF DISCHARGE AND RELATIVE JET VELOCITY.
○=Data from Series Fm △=Data from Series Cg

The theoretical pressure on the bucket as given by equation 26 (assuming $\alpha = 180°$), multiplied by the bucket efficiency and decreased by the measured pressure on the bucket, gives the loss of pressure due to windage and journal friction.

The computation is shown in Table III for series Fm and in Table IV for series Cg.

TABLE III

SERIES FM. FULL VALVE OPENING. HEAD = 153.5' q = .344.

R. P. M.	Actual pressure on buckets.	ϕ	$(1 - \phi)$ q.	$(1 - \phi)\sqrt{2gh}$	Theoretical pressure on bucket.	Efficiency of bucket.	Calculated pressure on bucket.	Windage and journal friction
1536.4	4	79.9	.0692	19.9	26.7	83.5	22.3	18.3
1313.0	20	69.2	.106	30.6	40.9	82.0	33.5	13.5
1153.4	32	59.1	.141	40.5	54.35	77.0	41.8	9.8
994.9	44	52.4	.164	47.2	63.25	80.0	50.6	6.6
808.9	56	42.6	.197	56.9	76.20	81.0	61.7	5.7
629.8	68	33.2	.230	66.3	88.8	80.0	70.7	2.7
410.4	80	21.8	.269	77.5	100.4	81.0	81.5	1.5
0.	107.5	0.	.344	99.2	132.75	81.0	107.5	0.

TABLE IV.

SERIES Cg. VALVE OPENING 66 PER CENT. HEAD = 83.7' q =.1654.

R. P. M.	Actual pressure on buckets.	ϕ	$(1 - \phi)$ q.	$(1 - \phi)\sqrt{2gh}$	Theoretical pressure on bucket.	Efficiency of bucket.	Calculated pressure on bucket.	Windage and journal friction.
1148	0	.818	.0301	13.35	8.59	92.	7.9	7.9
1042	4	.743	.0425	18.84	12.13	90.	10.92	6.92
904	10	.644	.0589	26.1	16.80	87.	14.62	4.62
584	22	.416	.0965	42.8	27.55	82.2	22.65	0.65
740	16	.527	.0783	34.7	22.30	83.3	18.60	2.60
366	28	.261	.1221	54.1	34.85	82.2	28.65	0.65
141	34	.1005	.1487	65.9	42.4	83.1	35.25	1.25
0	38.87	0.	.1654	73.3	47.2	82.7	39.0	0.

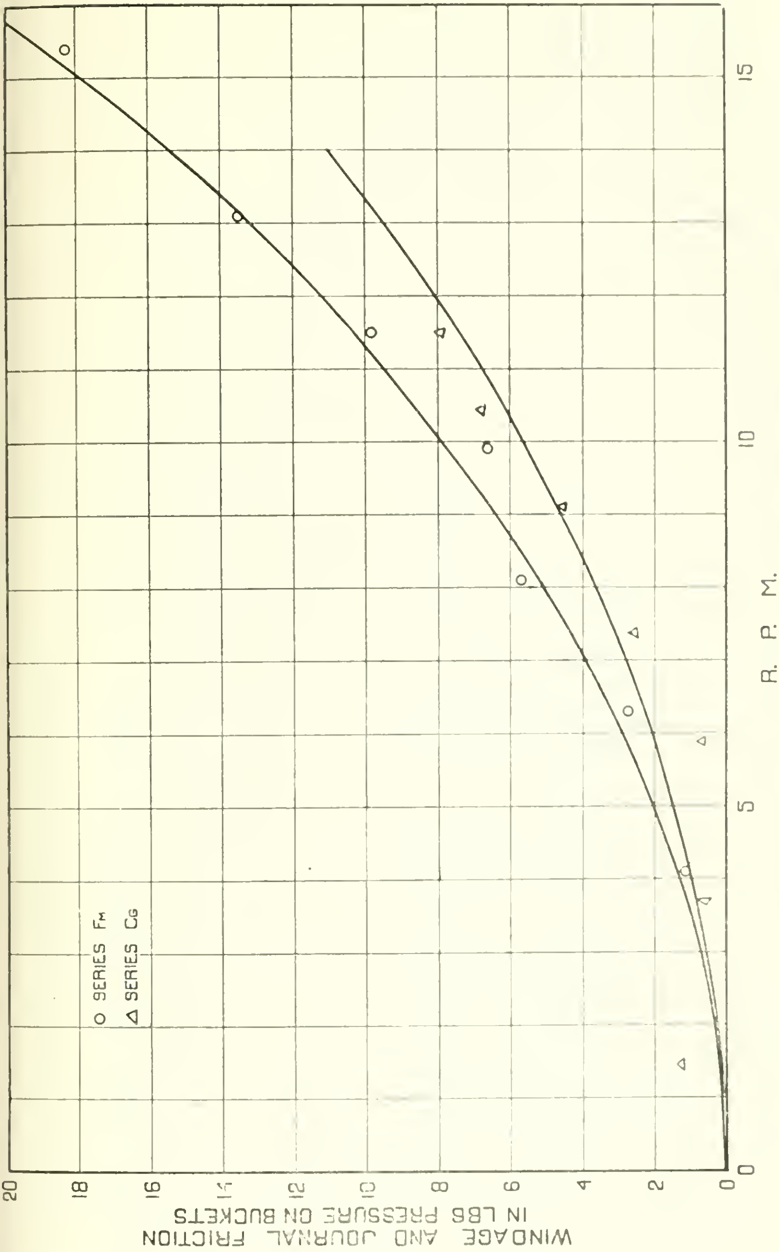


Figure 13.—Relation of Journal Friction and Windage to R. P. M.

Fig. 13 shows the windage and friction effect as a function of the r. p. m. of the wheel, and Fig. 14 shows this for series Fm in terms of the square of the r. p. m. It is evident from both figures that the pressure on the bucket required to maintain a given speed of the runner without other load than that due to journal friction and windage varies as the square of the speed of rotation.

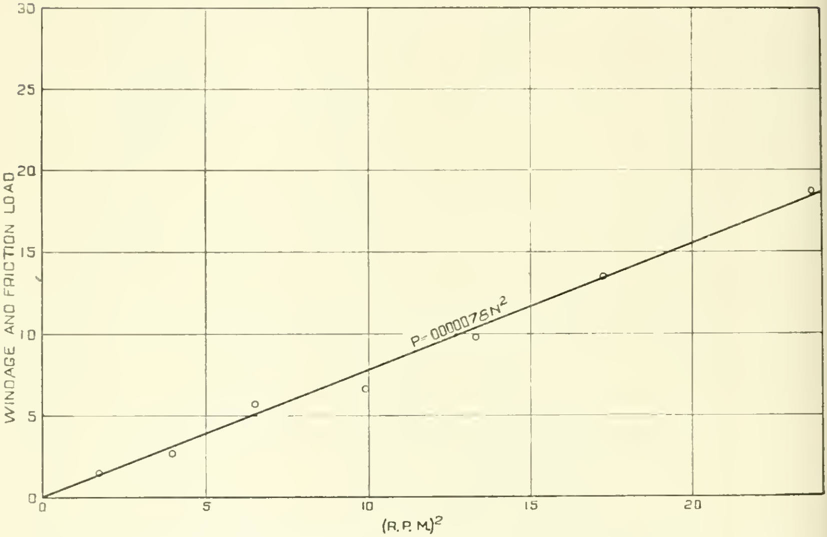


FIGURE 14.—RELATION OF JOURNAL FRICTION AND WINDAGE TO THE SQUARE OF THE R. P. M.

Based on equation 26 we may write an equation for the actual efficient pressure on the buckets under various speeds as follows:

$$F_a = \frac{2.825\, q w \sqrt{h}}{\sqrt{g}} (1 - \phi)\, e - n^2 r'. \tag{27}$$

In the equation

$$p = r'n^2$$

from the two series of experiments which were investigated,

$r' = .0000078\, n^2$ (From Series Fm).

$r' = .0000056\, n^2$ (From Series Cg).

EFFECT OF DIAMETER OF WHEEL AND NOZZLE ON POWER

As the power delivered to the wheel varies with the discharge of the nozzle (equation 18) $P_e = \frac{qwh}{550}$, and the discharge varies with the area of the nozzle (equation 2) $q = ca\sqrt{2gh}$, it is evident that with nozzles of homogeneous designs, that is with nozzles so constructed that the coefficient of discharge (c) for various openings will remain constant for each condition of gate opening, the discharge of the wheel and therefore the power of the wheel will vary directly with d^2 where d is the diameter of the nozzle.

It is also evident that the relation of the diameter of the jet to the size of the bucket is important and that the size of the bucket must also increase with the increased diameter of the nozzle if the same efficiency is to be maintained. The efficiency and power of the wheel depend on the relative velocity of bucket and jet. The diameter of the tangential wheel, therefore, has no theoretical effect on its power but only on the number of revolutions per minute.

DEVELOPMENT OF MECHANICAL ENERGY

The purpose of the tangential wheel is to convert the energy of water into mechanical energy. The energy of the water, in foot pounds per second, is (see equation 18),

$$E_1 = qwh.$$

The mechanical energy developed at the turbine shaft as measured by the Prony brake, in foot pounds per second, is given by the equation

$$E_a = \frac{2\pi Lnl}{60 \times 16}. \quad (28)$$

In equation 28, L is the brake resistance in ounces, as indicated on the scales, and $\frac{2\pi nl}{60}$ is the space passed through or displacement per second of which $\frac{2\pi l}{60}$ is a constant. The relations between (L) and (n), as determined by the experiments, and the relations actually found to exist between resistance and speed under a 95 foot head and at the various gate openings, are shown in Fig. 15.

EFFECTS OF SPEED ON POWER

The conditions that exist in the tangential wheel under operation are essentially as follows: The water leaves the nozzle with a velocity, v, and acts on a moving surface of the bucket. If no friction loss were sustained, the wheel would acquire a velocity equal to the moving jet of water,—that is to a theoretical velocity equal to that due to the head. As there are necessarily friction losses in all wheels, the actual speed of the bucket will always be less by a certain percentage of velocity, which is lost in overcoming the friction of the wheel, windage, bucket losses, etc. The velocity of the bucket or wheel, to which reference is here made, must be measured at the center or point of application of the jet acting on the wheel. This, in the tangential wheel, is practically at the center of the hydraulic surface of the bucket. Under the theoretical condition of a frictionless wheel, it is evident that when the resultant velocity of the water and of the buckets of the wheel are the same, the water can produce no pressure on the buckets and the wheel can deliver no power. It is also evident that in actual operation of the wheel when the velocity of the wheel is such that the impulse of the jet is only sufficient to create the pressure on the bucket necessary to overcome the friction and other losses that the wheel can deliver no power.

Reduction in Maximum Speed at Part Gate

In a frictionless wheel the maximum velocity of the wheels should be equal to the velocity of the water and the same at all gate openings under a fixed head, for the velocity of the jet of water from any nozzle opening would be theoretically the same under all openings.

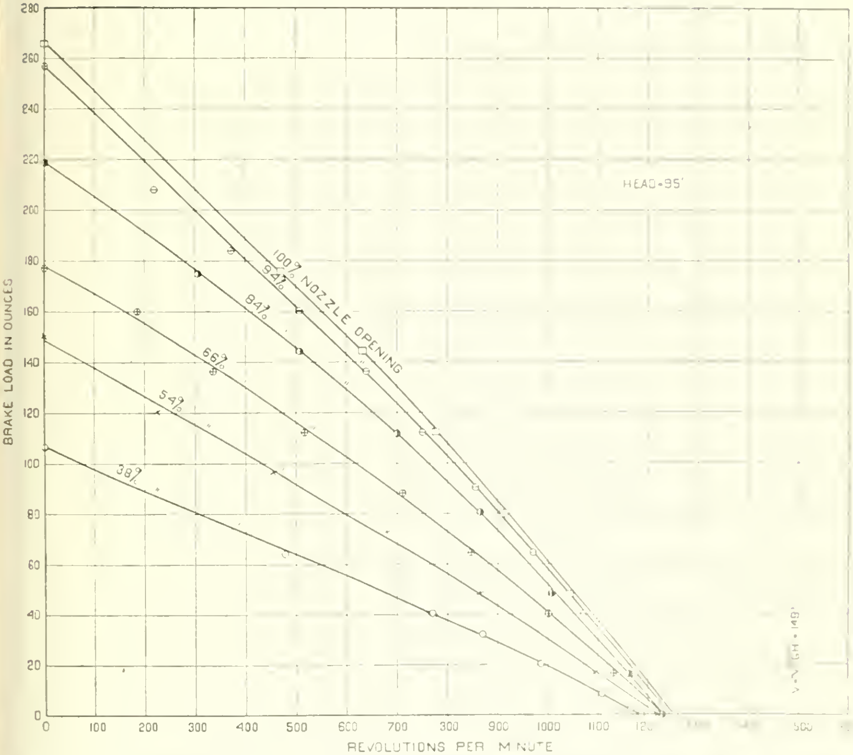


Figure 15.—Relation Between Resistance and Speed Under 95-Foot Head.

In the actual wheel (see equation 18).

$$E_1 = qwh.$$

As (q) is modified by the gate opening, and as the friction and windage of the wheel are fairly constant, a greater proportion of the energy of the jet at part gate is absorbed in overcoming these losses than at full gate, and therefore the maximum speed of the wheel at part gate is less than at full gate.

RELATION OF SPEED AND RESISTANCE

As soon as resistance occurs, the speed of the wheel will be reduced in order that the momentum of the water may be converted into pressure. This pressure will increase as the speed or the velocity of the bucket decreases until the maximum pressure results when the bucket is at rest. These conditions are illustrated in the experiment on the 12″ Doble wheel and are shown in Fig. 15 in which the resistance, L, is measured as ordinate, and the number of revolutions per minute, n, is measured as abscissas.

RELATION OF SPEED AND POWER

The actual space passed through by the resistance (L) is the number of revolutions per minute (n) multiplied by 2πl, and the actual power generated by the wheel will be (from equation 28)

$$P_a = \frac{L}{16} \times \frac{2\pi l n}{33000}. \tag{29}$$

Fig. 16 shows the actual horse power developed by the wheel under 95 ft. head and with various conditions of nozzle opening.

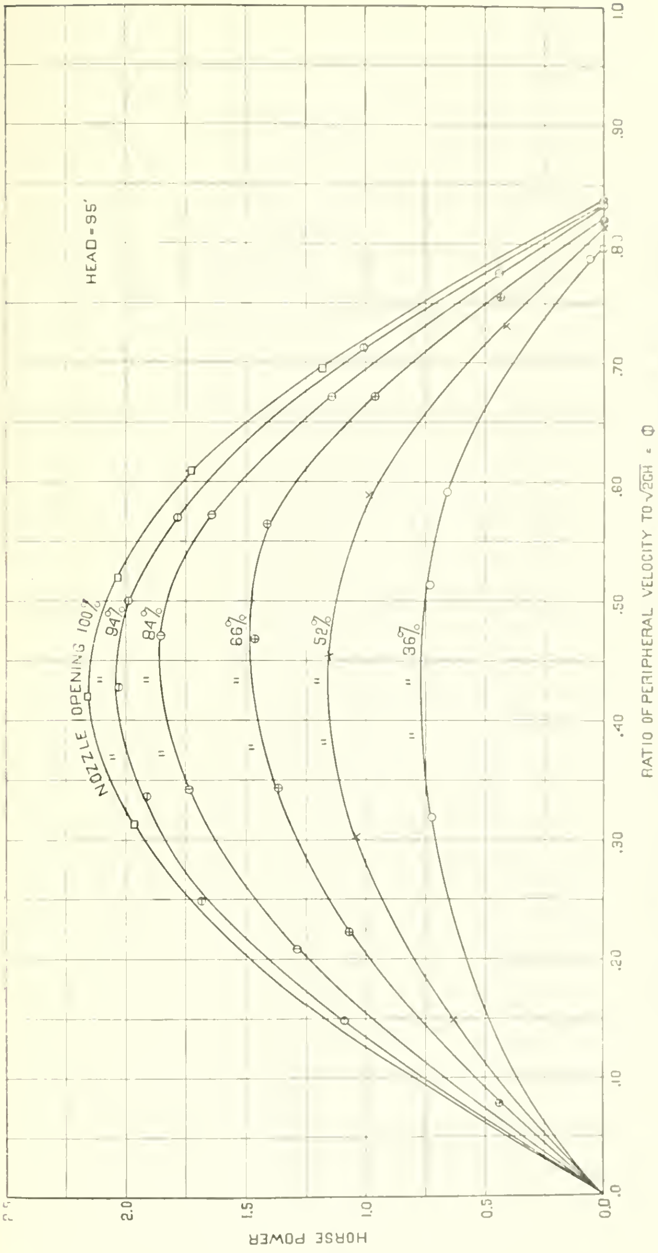


FIGURE 16.—RELATION BETWEEN POWER AND SPEED UNDER 95-FOOT HEAD.

BASIS FOR COMPARISON OF EXPERIMENTS UNDER VARIOUS HEADS

From equations 1 and 11

$$\phi = \frac{v'}{v} = \frac{v'}{\sqrt{2gh}}.$$

The velocity of the periphery of the wheel may be expressed by

(30) $$v' = \frac{D\pi n}{12 \times 60} = \frac{D\pi n}{720}.$$

Hence

(31) $$\phi = \frac{D\pi n}{720\sqrt{2gh}} = .000543\frac{Dn}{\sqrt{h}} = .000543\ Dn_1$$

and

(32) $$\frac{Dn}{\sqrt{h}} = Dn_1 = 1842\ \phi.$$

As (D) is constant for any given wheel, the revolutions under one foot head (n_1) vary directly with ϕ, and hence conditions under various heads may be readily compared by reducing the revolution of the experiment to the comparative revolutions at one foot head, which should be similar for all similar values of ϕ.

The pressure on the bucket is theoretically (see equation 10)

$$F = \frac{2qwv}{g}(1 - \phi).$$

Combining this equation with Equations 1 and 2,

(33) $$F = 4wcah\ (1 - \phi).$$

Hence, as 4wca is constant for the same nozzle opening, the pressure, F, should vary directly with h, if ϕ is constant, and in order to compare experiments at different heads, the pressure, F, may be reduced to the corresponding pressure at one foot head and should be found constant if ϕ is constant.

The brake load, L, which is the experimental measure of the pressure, F, and differs from it only by friction loss and windage is reducible in the same manner.

From these principles it is apparent that if the experiments made under various heads be reduced to the corresponding resistance and revolutions under one foot head, that the results of all experiments should for similar relations of ϕ and valve opening, correspond within the limits of experimental error.

Relation of Experimental Speed and Resistance

Figs. 17 to 22 show the results of the entire series of experiments with the wheel reduced to the basis of one foot head,—that is

$$\frac{L}{h} = L_1 \quad \frac{n}{\sqrt{h}} = n_1.$$

These diagrams show that the experiments when so reduced and platted correspond fairly well with the exception of certain experiments at the low heads and small nozzle opening.

An examination of the records of these individual experiments shows that the value of $\frac{q}{\sqrt{h}}$ for these experiments was considerably below the average, and that either the nozzle opening was obstructed by foreign matter caught in the nozzle or by an error in setting the valve, or that there was an error in measuring the head which was the cause of the apparent departure from the general law demonstrated by the other experiments.

The general agreement is sufficiently close to furnish a practical demonstration of the validity of the law expressed by equations 26, 32, and 33.

The Equation of Experimental Curves

The theoretical equation of an experimental curve can be determined with as great a degree of accuracy as may be desirable by the general form of equation

(34) $$x = a + by + cy^2 + dy^3 + \text{etc.}$$

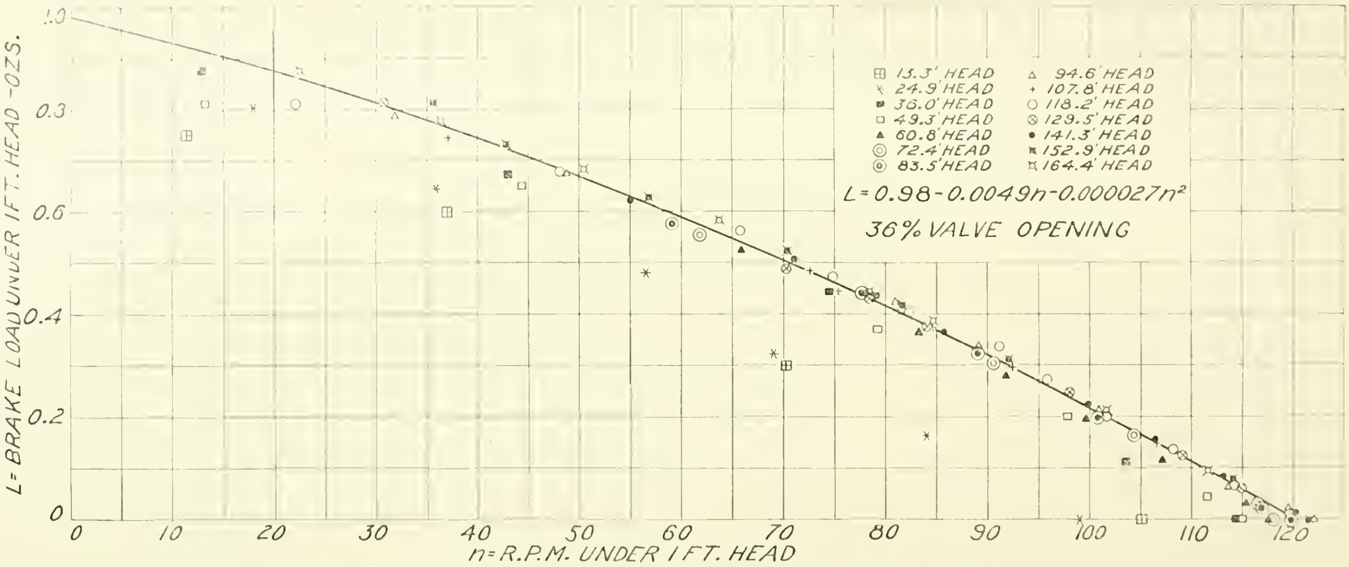


Figure 17.—Relation of Resistance to Speed for Various Nozzle Openings for All Experiments Reduced to Basis of One Foot Head.

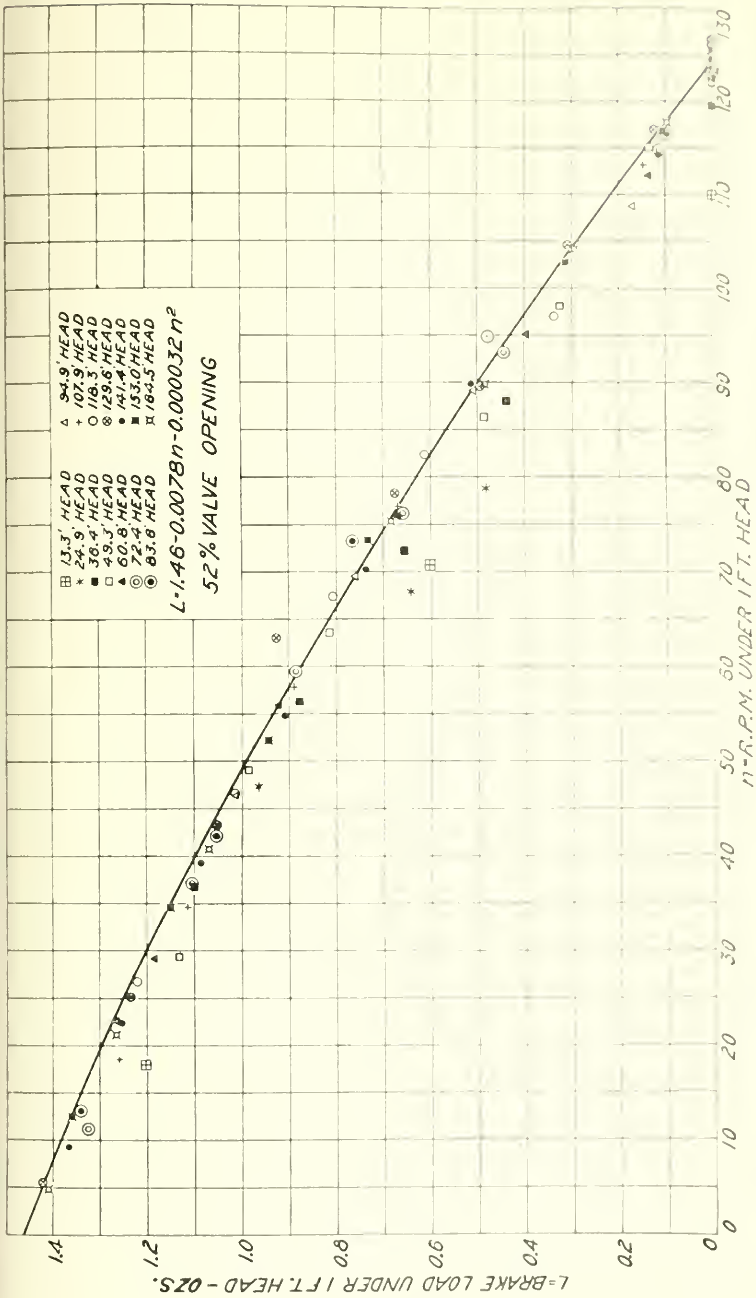


FIGURE 18.—RELATION OF RESISTANCE TO SPEED FOR ALL EXPERIMENTS REDUCED TO BASIS OF ONE FOOT HEAD.

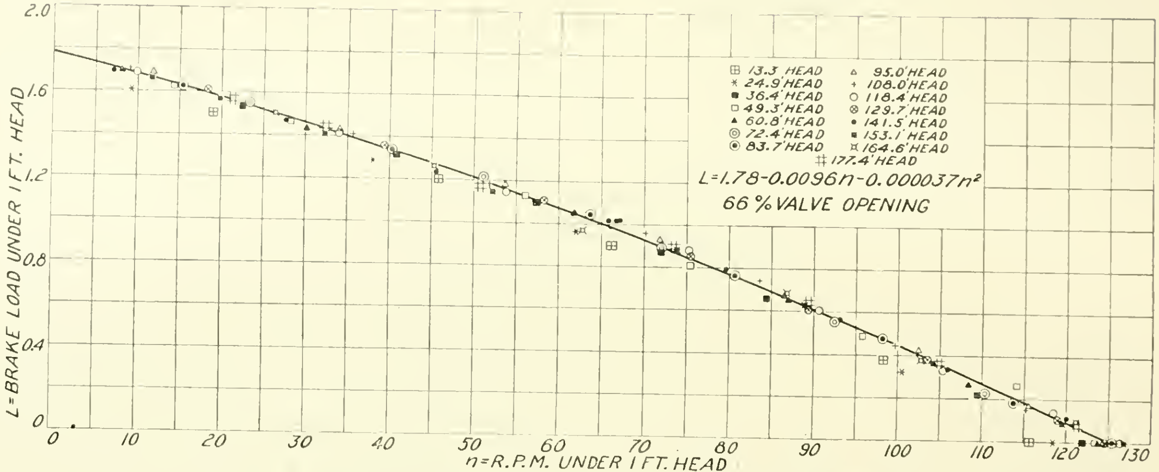
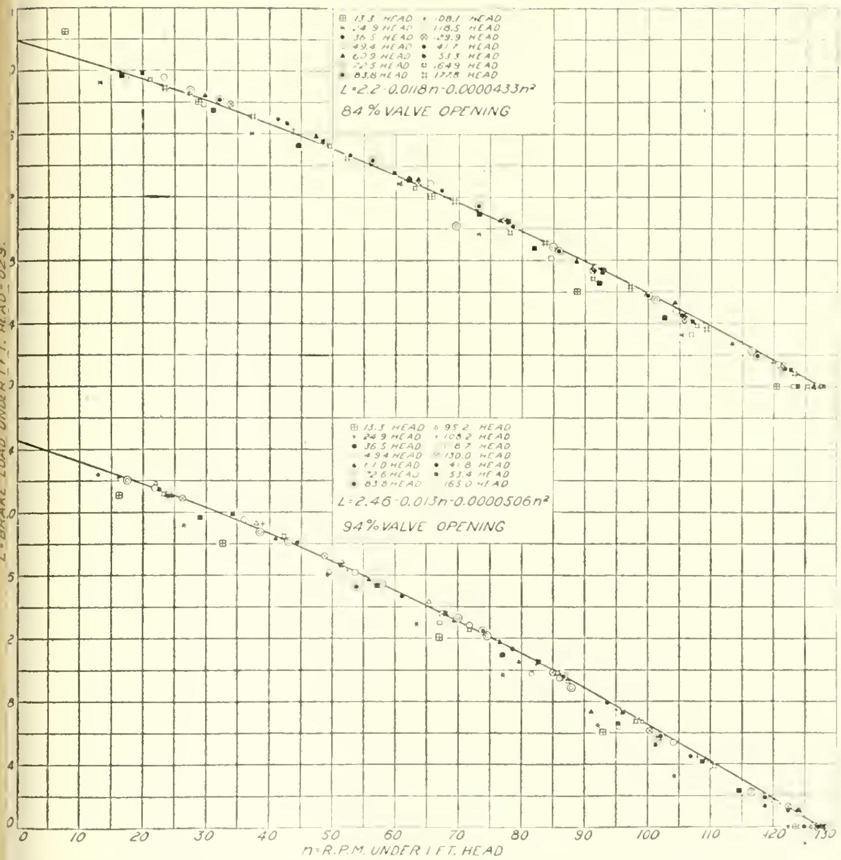


FIGURE 19.—RELATION OF RESISTANCE TO SPEED FOR VARIOUS NOZZLE OPENINGS FOR ALL EXPERIMENTS REDUCED TO BASIS OF ONE FOOT HEAD.



GURES 20 AND 21.—RELATION OF RESISTANCE TO SPEED FOR VARIOUS NOZZLE OPENINGS FOR ALL EXPERIMENTS REDUCED TO BASIS OF ONE FOOT HEAD.

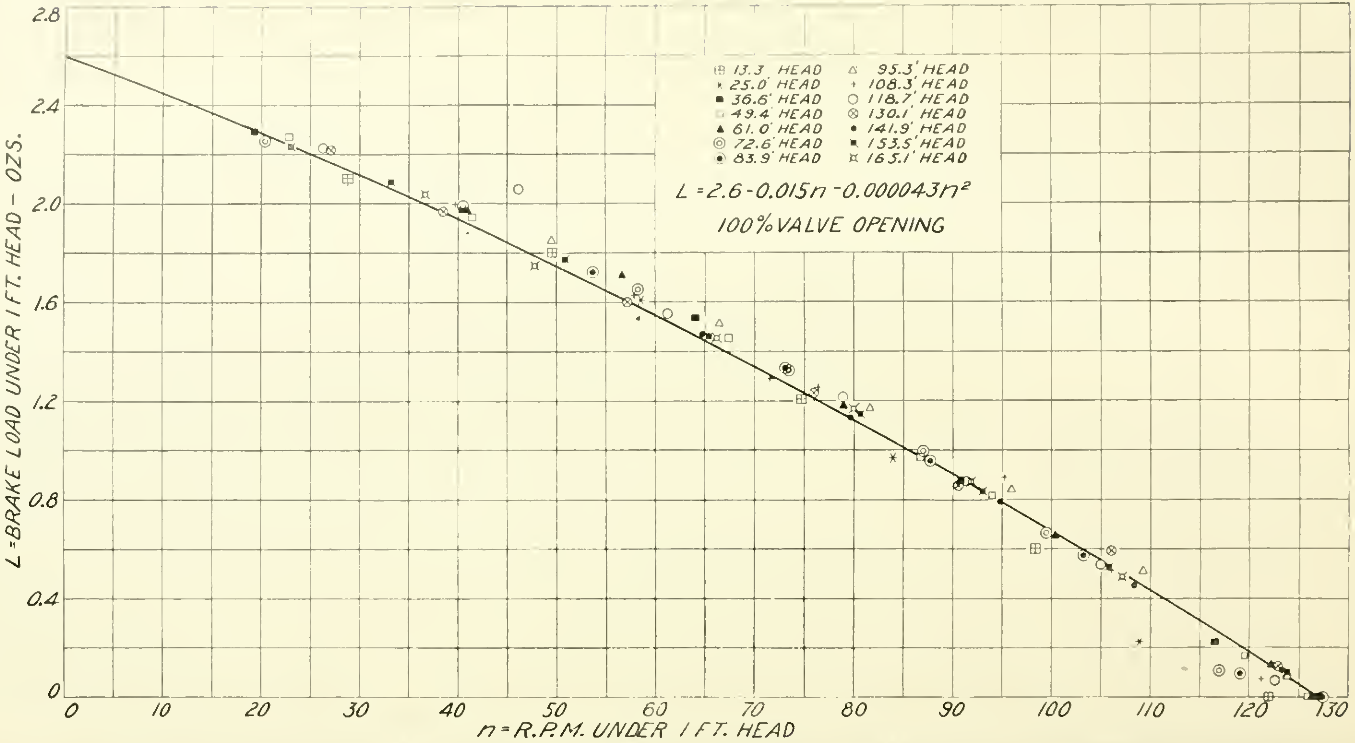


Figure 22.—Relation of Resistance to Speed for Various Nozzle Openings for All Experiments Reduced to Basis of One Foot Head.

Having therefore platted any series of experiments which are apparently governed by some uniform law but which may through experimental errors depart more or less therefrom, the curve which represents the apparent law of variation between any two variables on which the law depends may be constructed by drawing a smooth curve through the means of the various experimental points, and an empirical equation may be determined therefrom by the selection of several points on the curve, the substitution of the value of x and y at the selected point in the above equations, and the solution of the equations thus formed, in order to determine the values of a, b, c, etc.

THE EQUATION OF THE RELATION OF RESISTANCE TO SPEED

In this way the relation between $\frac{L}{h}$ and $\frac{n}{\sqrt{h}}$ for the equations representing these relations has been derived in the form

$$L_1 = a + bn_1 + cn_1^2. \tag{35}$$

The equation derived for each curve is shown on the diagram of the curve in question.

THE EQUATION OF THE RELATION OF POWER AND SPEED

From equation (28)

$$E_a = \frac{2\pi lLn}{60 \times 16} \text{ from which}$$

$$P_a = \frac{2\pi lLn}{550 \times 60 \times 16} \tag{36}$$

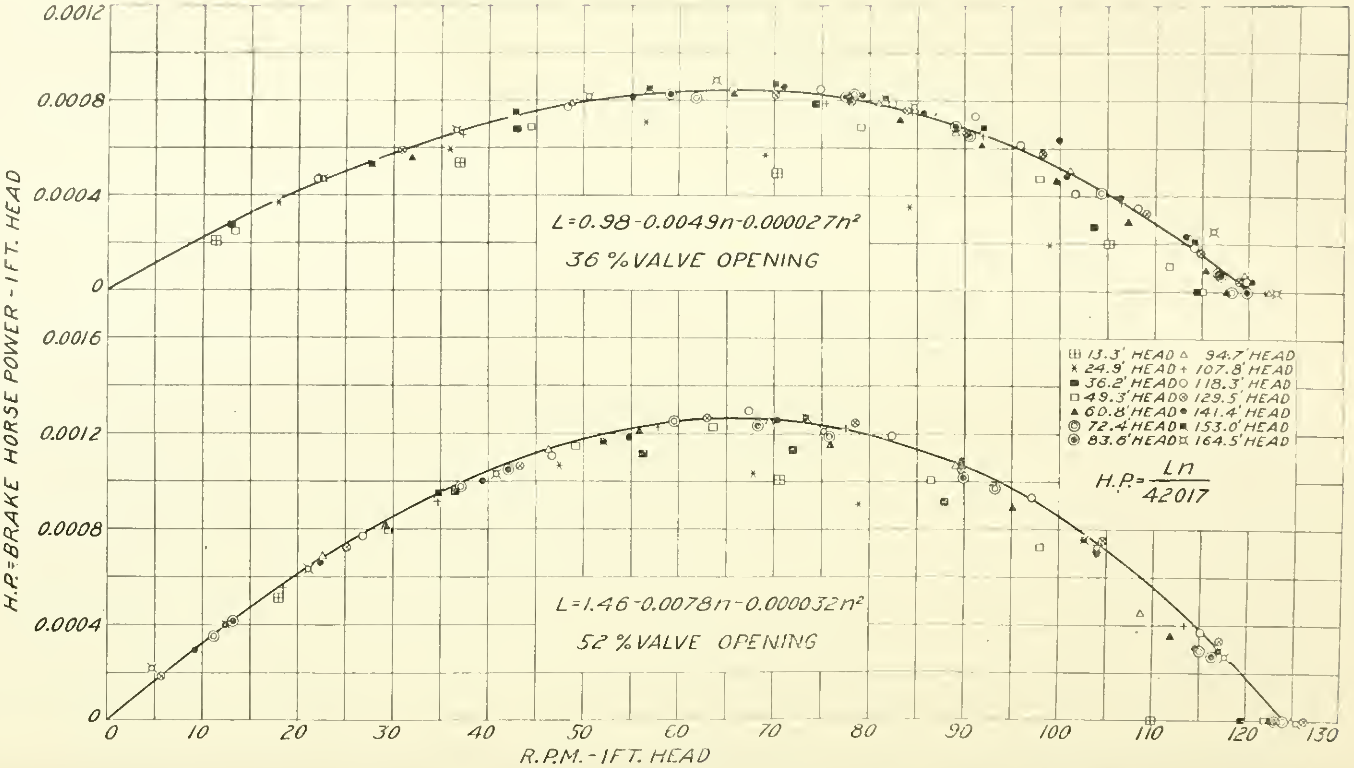
and the horse power under one foot head will be

$$P_{a_1} = \frac{2\pi l}{550 \times 60 \times 16} L_1 n_1 = \frac{L_1 n_1}{42017}. \tag{37}$$

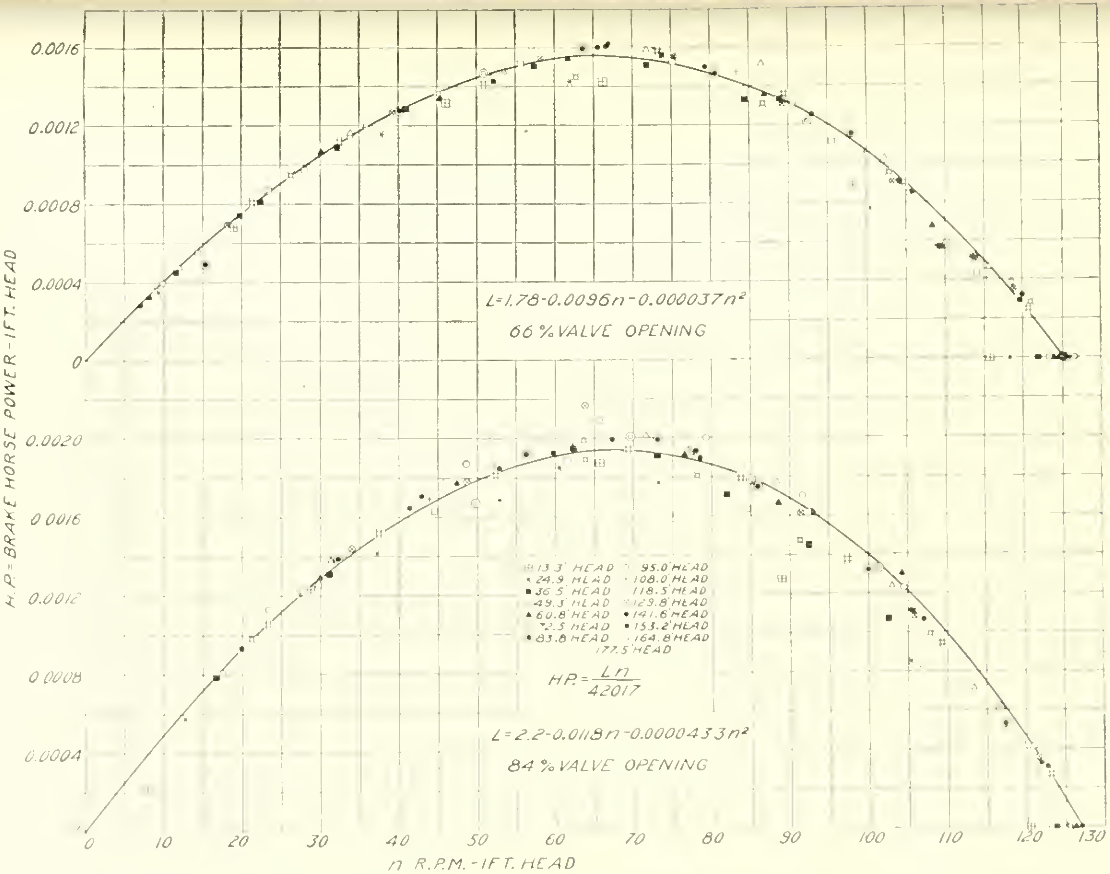
Having the value of L_1 as given in equation (35), the formula P_{a_1} becomes

$$P_{a_1} = \frac{an_1 + bn_1^2 + cn_1^3}{42017}. \tag{38}$$

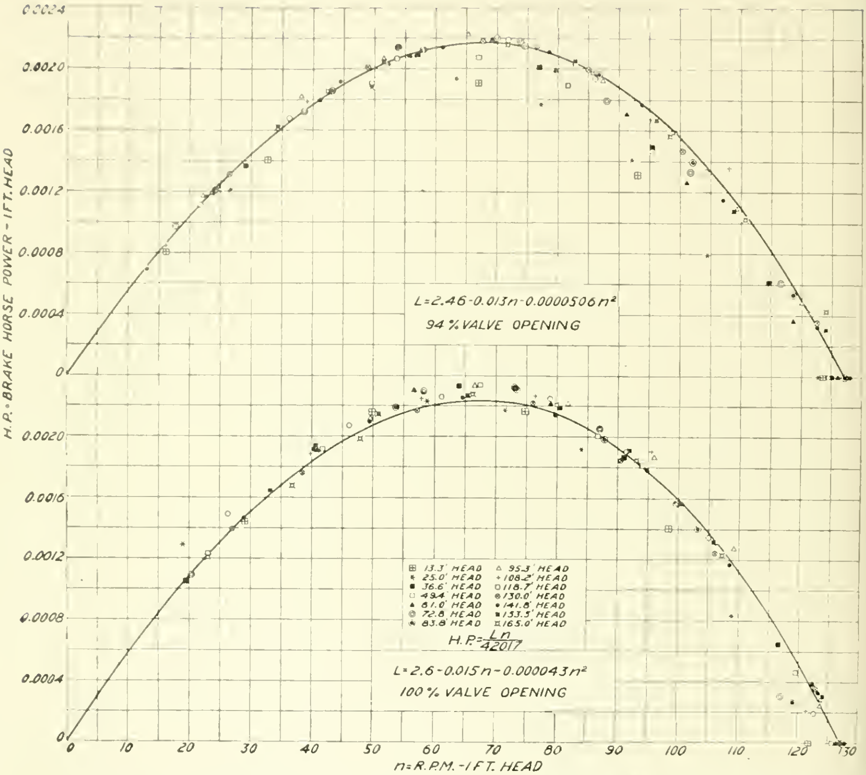
The relation of power to speed at all heads and under the six conditions of gate opening has been platted in Figs. 23 to 28, and the experimental curve for each condition corresponding to equation 38 has been platted.



FIGURES 23 AND 24.—RELATION OF POWER TO SPEED FOR ALL EXPERIMENTS AND FOR VARIOUS NOZZLE OPENINGS REDUCED TO BASIS OF ONE FOOT HEAD.



FIGURES 25 AND 26. RELATION OF POWER TO SPEED FOR ALL EXPERIMENTS AND FOR VARIOUS NOZZLE OPENINGS REDUCED TO BASIS OF ONE FOOT HEAD



FIGURES 27 AND 28.—RELATION OF POWER TO SPEED FOR ALL EXPERIMENTS AND FOR VARIOUS NOZZLE OPENINGS REDUCED TO BASIS OF ONE FOOT HEAD.

THE EQUATION FOR MAXIMUM POWER

To ascertain the speed at which the maximum power can be obtained from a wheel, the first differential of equation 38 relative to n can be taken and made equal to 0.

$$\frac{d\,(P_{a_1})}{dn_1} = \frac{(a + 2bn_1 + 3\,cn_1{}^2)}{12017} = 0. \tag{39}$$

This equation solved for n will give the speed for maximum power at one foot head, and, if multiplied by $\sqrt{h}$, will give the speed for maximum power at any given head, h.

THE POWER OF THE WHEEL

The power which may be developed by any wheel depends on the head available, the quantity of water which may be discharged against the buckets under that given head and at the given gate opening, and the relation of speed and resistance under which the wheel will operate.

It has already been shown that, with a given gate opening, $\frac{qw}{\sqrt{h}}$ is a constant for all heads; also, that the resistance (L) varies with $\frac{n}{\sqrt{h}}$. As $\frac{n}{\sqrt{h}}$ varies directly with ϕ, the resistance factor is always the same when the gate opening and the value of ϕ remain constant.

The horse power of the water applied to the wheel is represented by equation 18.

$$P_e = \frac{qwh}{550}.$$

The horse power developed by the wheel is represented by equation 29.

$$P_a = \frac{2\pi Ln}{33000 \times 16}.$$

THE EQUATION FOR RELATIVE AND MAXIMUM EFFICIENCY

The efficiency of the wheel is the relation of theoretical horse power, P_e to the actual horse power, P_a, i. e.

$$e_a = \frac{P_a}{P_e} = \frac{2\pi lLn}{16 \times 60\, qwh} \tag{40}$$

and for one foot head

$$e_{a_1} = \frac{(an_1 + bn_1^2 + cn_1^3)\, 550}{42017\, q_1 wh_1} \quad \text{or}$$

$$e_{a_1} = \frac{an_1 + bn_1^2 + cn_1^3}{4775\, q_1}. \tag{41}$$

The essential truth of this law is shown by these experiments and is illustrated in Figs. 29 to 34 inclusive in which the efficiency of the wheel at various conditions of head is shown by the ordinate and $\frac{n}{\sqrt{h}}$ by the abscissae.

The first differential of equation 41 will give the most efficient speed, and as the first differentials of equations 38 and 41 are the same, the speeds for maximum power and maximum efficiency are therefore the same.

POWER OF WHEEL UNDER VARIOUS HEADS

The horse power delivered to a wheel is, from equation 18,

$$P_e = \frac{qwhe}{550}.$$

From equation (2)

$$q = ca\sqrt{2gh}.$$

Combining these equations

$$P_e = \frac{caw\sqrt{2g}\, h^{3/2}\, e}{550}. \tag{42}$$

From this equation it is apparent that if c, e, and a are constant for any given wheel and for any fixed gate opening, and if the value of ϕ remains constant, the power of the turbine will be directly proportional to $h^{3/2}$. This law is also demonstrated

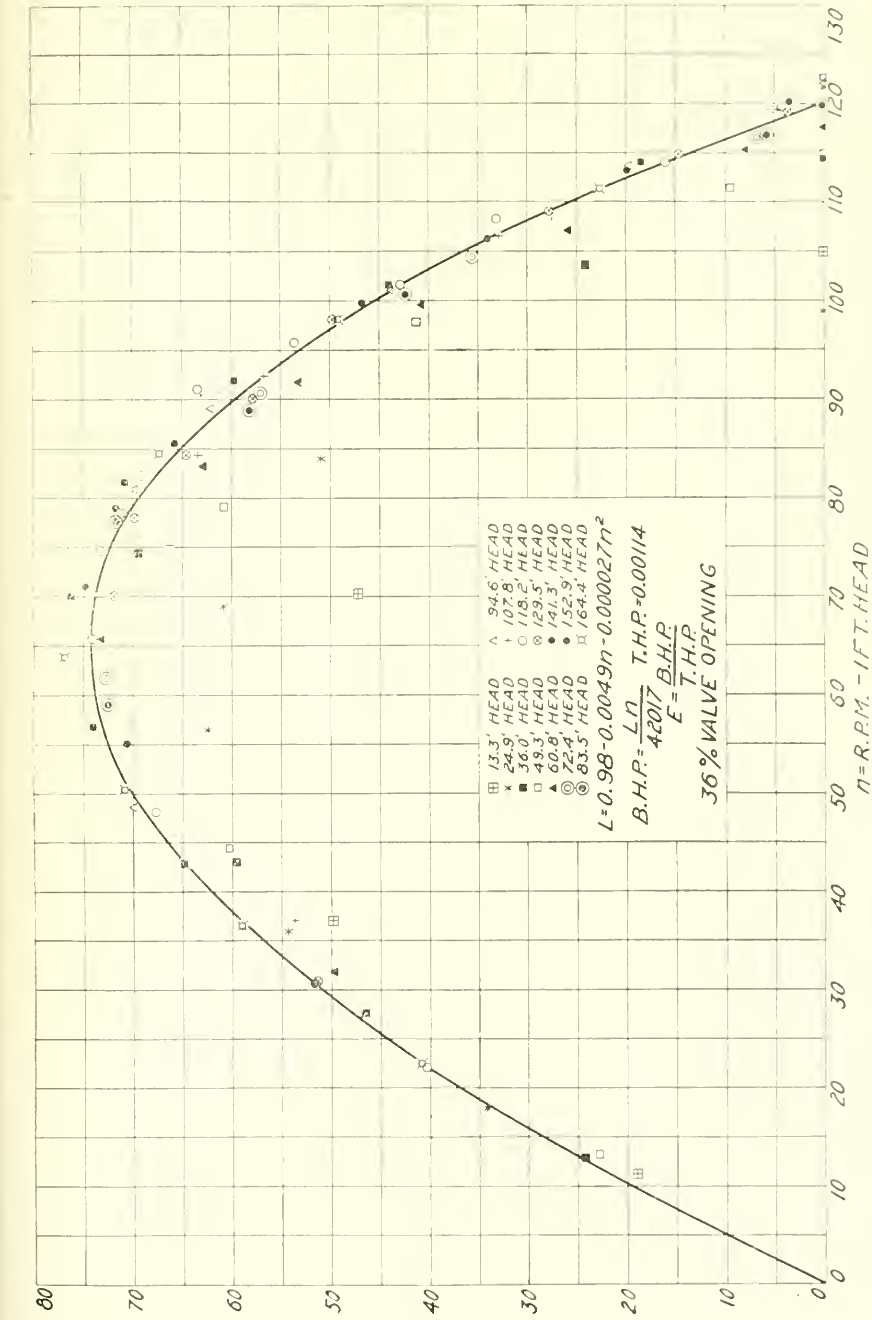


FIGURE 29.—RELATION OF EFFICIENCY TO SPEED FOR ALL EXPERIMENTS AND FOR 36 PER CENT NOZZLE OPENING REDUCED TO BASIS OF ONE FOOT HEAD.

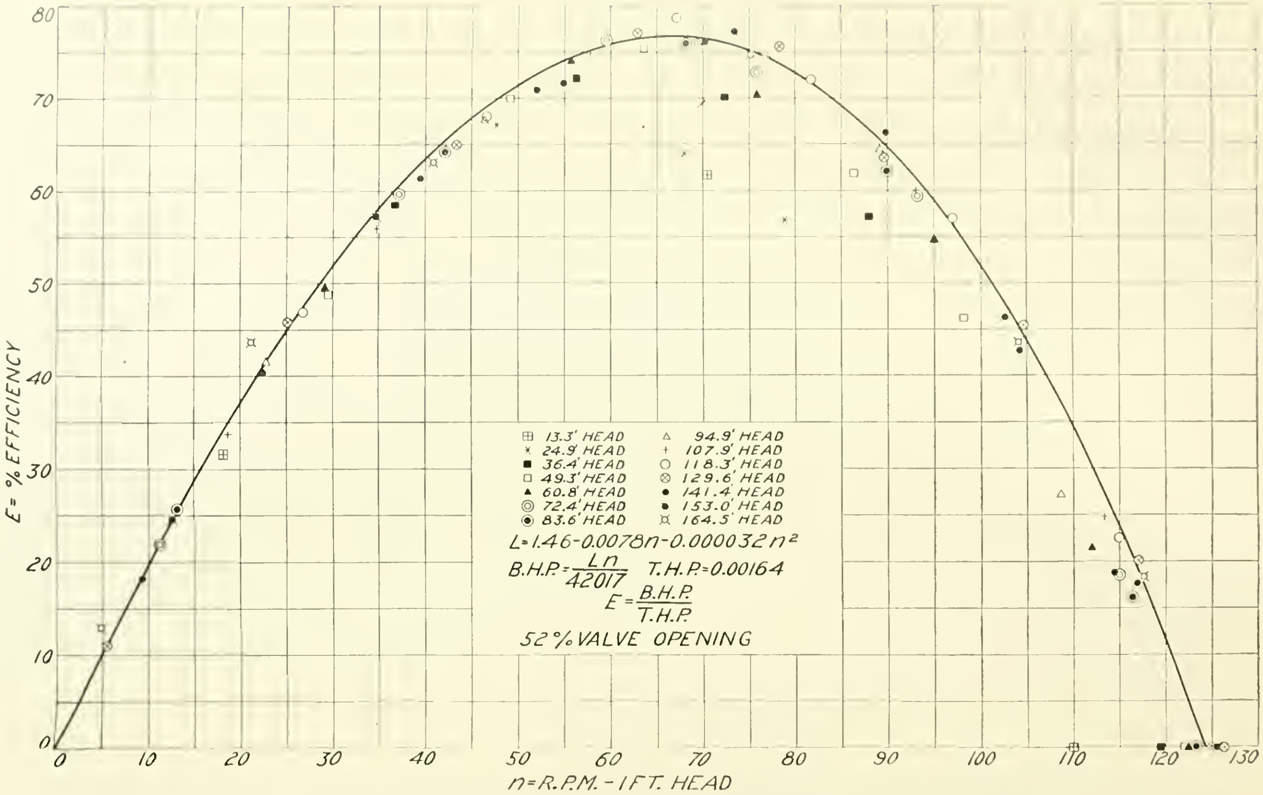


FIGURE 30.—RELATION OF EFFICIENCY TO SPEED FOR ALL EXPERIMENTS AND FOR 52 PER CENT NOZZLE OPENINGS REDUCED TO BASIS OF ONE FOOT HEAD.

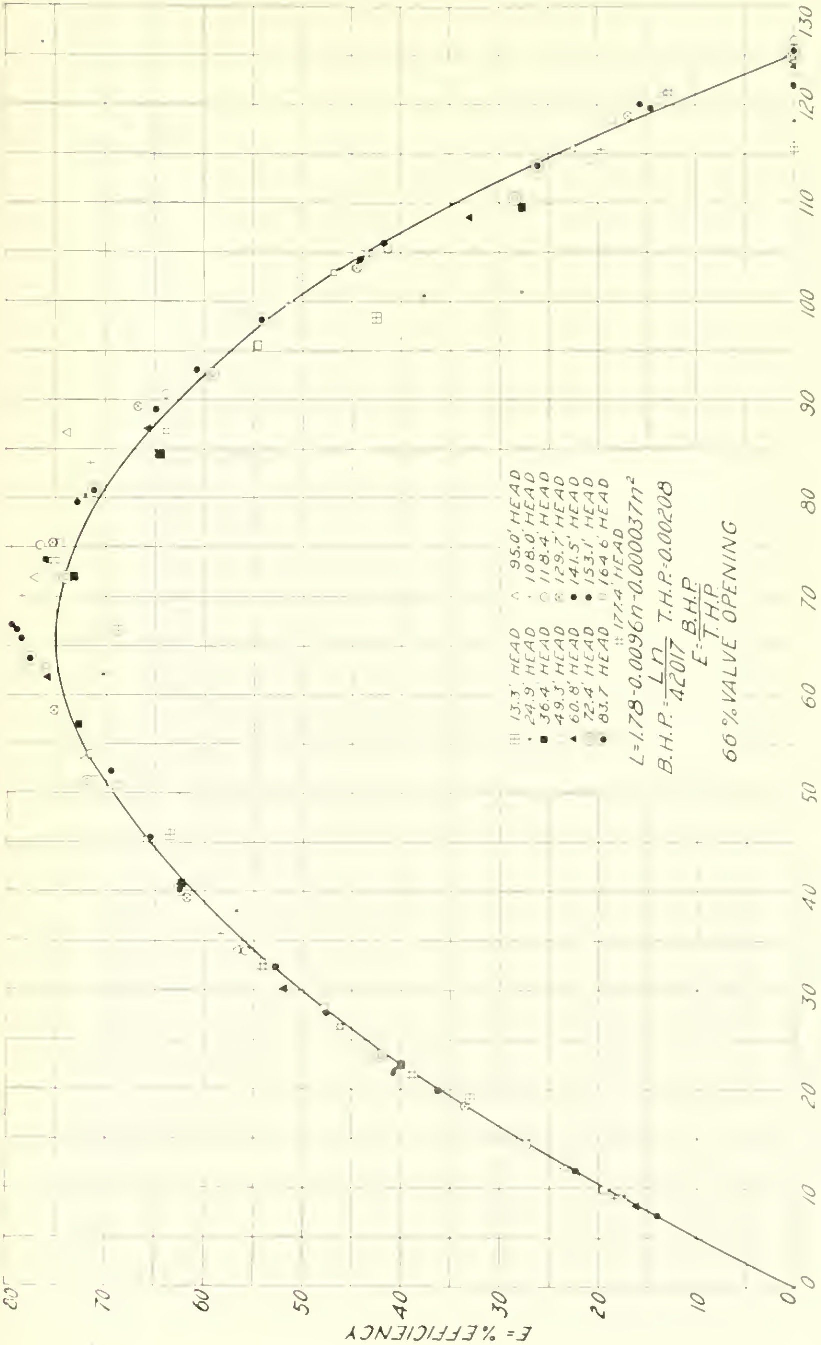


FIGURE 31.—RELATION OF EFFICIENCY TO SPEED FOR ALL EXPERIMENTS AND FOR 66 PER CENT NOZZLE OPENING REDUCED TO BASIS OF ONE FOOT HEAD.

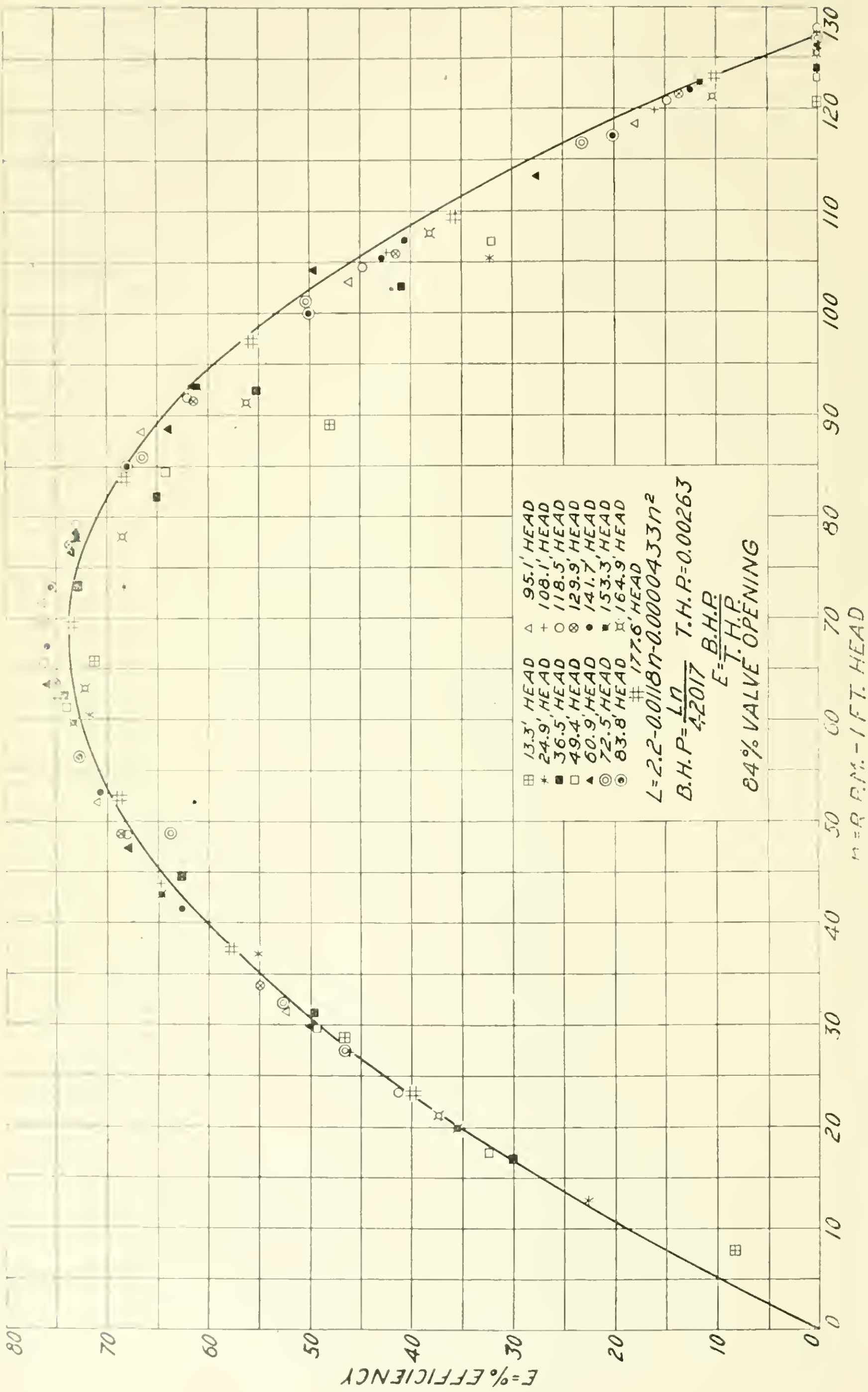


Figure 32.—Relation of Efficiency to Speed for All Experiments and for 84 Per Cent Nozzle Opening Reduced to Basis of One Foot Head.

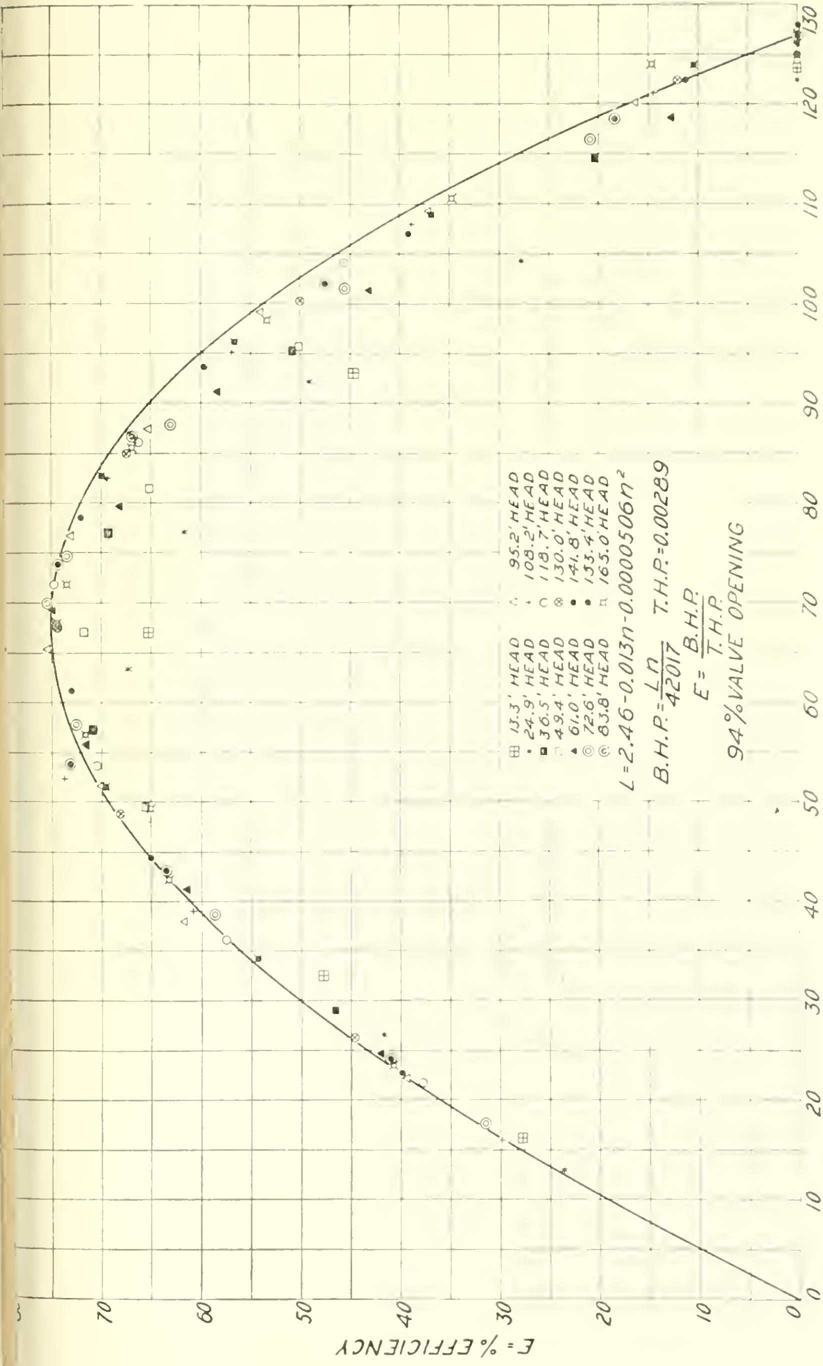


FIGURE 38.—RELATION OF EFFICIENCY TO SPEED FOR ALL EXPERIMENTS AND FOR 94 PER CENT NOZZLE OPENING REDUCED TO BASIS OF ONE FOOT HEAD.

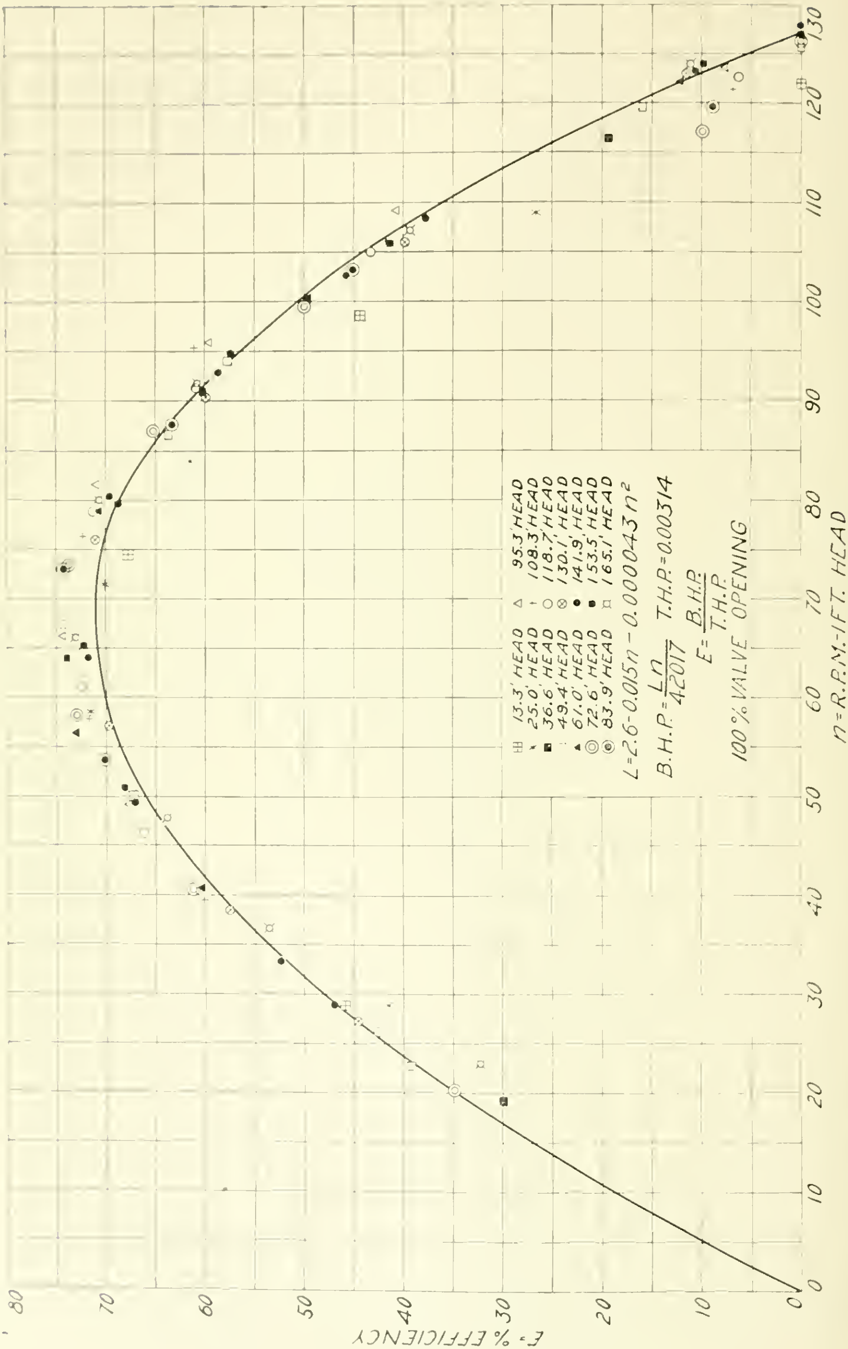


FIGURE 34.—RELATION OF EFFICIENCY TO SPEED FOR ALL EXPERIMENTS AND FOR FULL NOZZLE OPENING REDUCED TO BASIS OF ONE FOOT HEAD.

by experiments herein discussed. The experiments illustrating this law have been platted in Figs. 35 to 40 inclusive in which are shown the theoretical curves representing the relation between head and power, under various conditions of gate and of head and power for various values of ϕ. The values of ϕ, and therefore the experimental curves, were obtained by reducing the equation $P = Ch^{3}/{}^{2}$ to the form of an equation for a straight line by substituting x for the values of $h^{3}/{}^{2}$, giving $P = Cx$, from which the value of C could be at once determined by substituting the values of P and x for a given point on the line selected. Having determined this value for C, and substituting in the equation $P = Ch^{3}/{}^{2}$, the theoretical relation between power and head could be at once determined for any value of ϕ. From these values the theoretical power lines were platted in Figs. 35 to 40 inclusive and the corresponding experimental points platted thereon. The close agreement between the theoretical line and the experimental point demonstrates the truth of the theoretical law.

GENERAL EQUATIONS FOR POWER

The equation for power under one foot head, 38,

$$P_{a_1} = \frac{an_1 + bn_1{}^2 + cn_1{}^3}{12017}$$

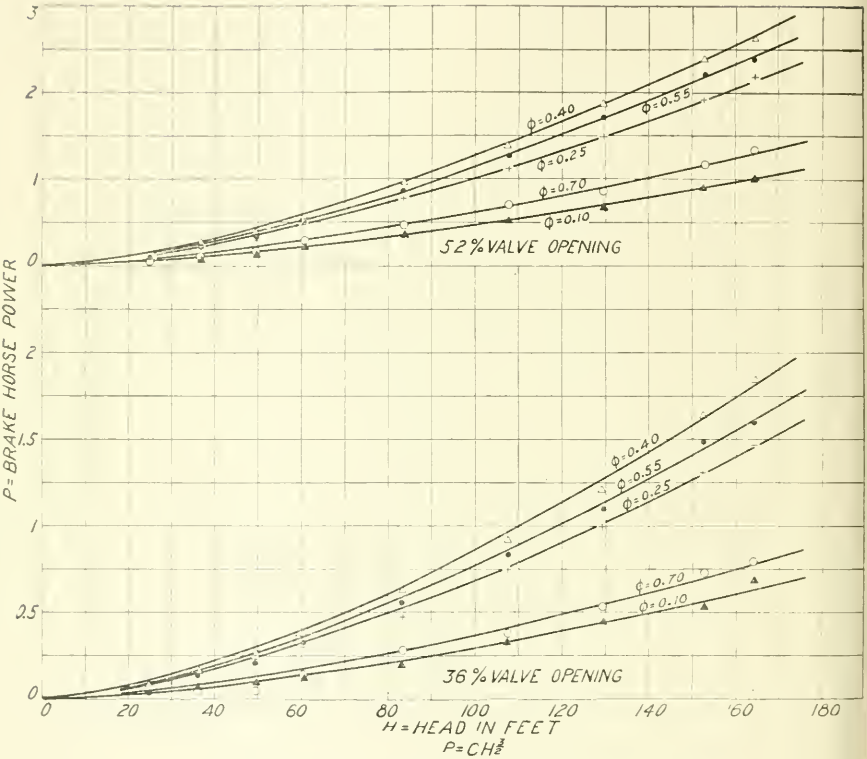
may be made general for power at any head by multiplying by $h^{3}/_{2}$ (see Equation 40); therefore

$$P_a = \frac{an_1 + bn_1{}^2 + cn_1{}^3}{12017} h^{3}/{}^{2}. \tag{43}$$

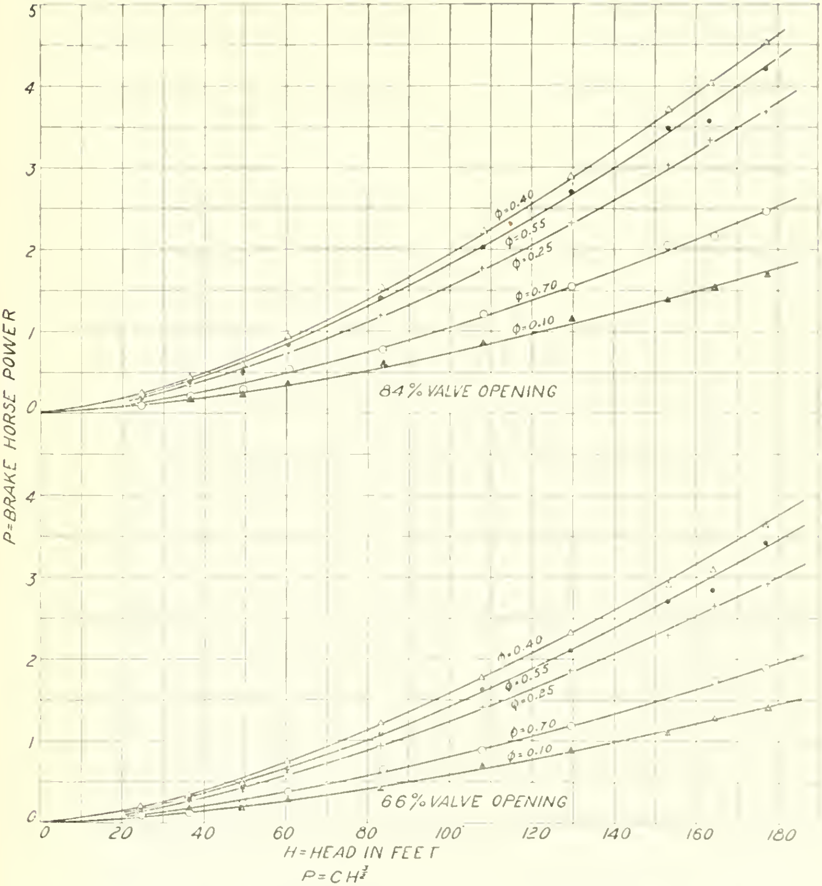
Equation for Theoretical Characteristic Curve

From Equation 14 the theoretical foot pounds per second which is recovered in an impulse wheel is

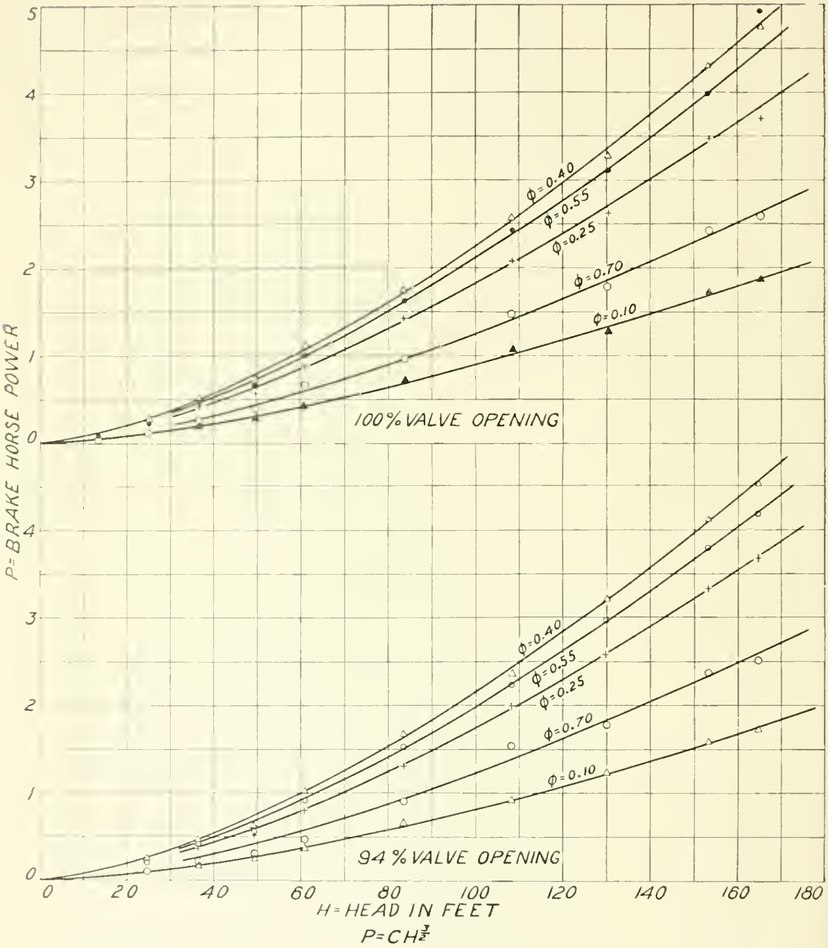
$$E_4 = (1 - \cos \alpha)\,(1 - \phi)\,\phi \frac{qwv^2}{g}.$$



FIGURES 35 AND 36.—RELATION OF POWER TO HEAD AT VARIOUS GATE OPENINGS AND FOR VARIOUS VALUES OF ϕ.



FIGURES 37 AND 38.—RELATION OF POWER TO HEAD AT VARIOUS GATE OPENINGS AND FOR VARIOUS VALUES OF ϕ.



FIGURES 39 AND 40.—RELATION OF POWER TO HEAD AT VARIOUS GATE OPENINGS AND FOR VARIOUS VALUES OF ϕ.

The actual energy supplied to the wheel is:

$$E_3 = \frac{qwv^2}{2g}.$$

Hence the efficiency is

$$e = 2(1 - \cos\alpha)(1 - \phi)\phi.$$

This equation represents the efficiency curves in the theoretical characteristic curve of the impulse wheel and is a parabola with vertex or point of maximum efficiency at

$$\phi = .5$$

and with zero efficiency at

$$\phi = 0 \text{ and } \phi = 1.$$

The theoretical characteristic curve is shown graphically in Fig. 41.

The curves of efficiency (full lines) are independent of q, and lines of equal efficiency are therefore parallel to the q axis. The lines of equal power (dotted lines) can be shown to have the equation: $(1 - \phi)\ \phi q = \frac{550\ P}{2w\ (1 - \cos\alpha)}$ where ϕ and q are the variables.

The Experimental Characteristic Curve

The actual relations of power, efficiency, speed and discharge under three different conditions of head are represented by the characteristic curves shown in Figs. 42, 43 and 44.

These curves are constructed by platting, the experimental points relative to ϕ or n_1 and q_1, writing beside the platted point the corresponding values of P_{a_1} and e_{a_1} for each experimental point, and interpolating lines of equal values of P_{a_1} and e_{a_1}; or, having interpolated the lines of equal efficiency, the position of the lines of equal power can readily be calculated from the theoretical discharge and the efficiency lines. In Figs. 41, 42, 43 and 44, the full lines are lines of equal efficiency, and the dotted lines of equal power. From these diagrams it will be noted that

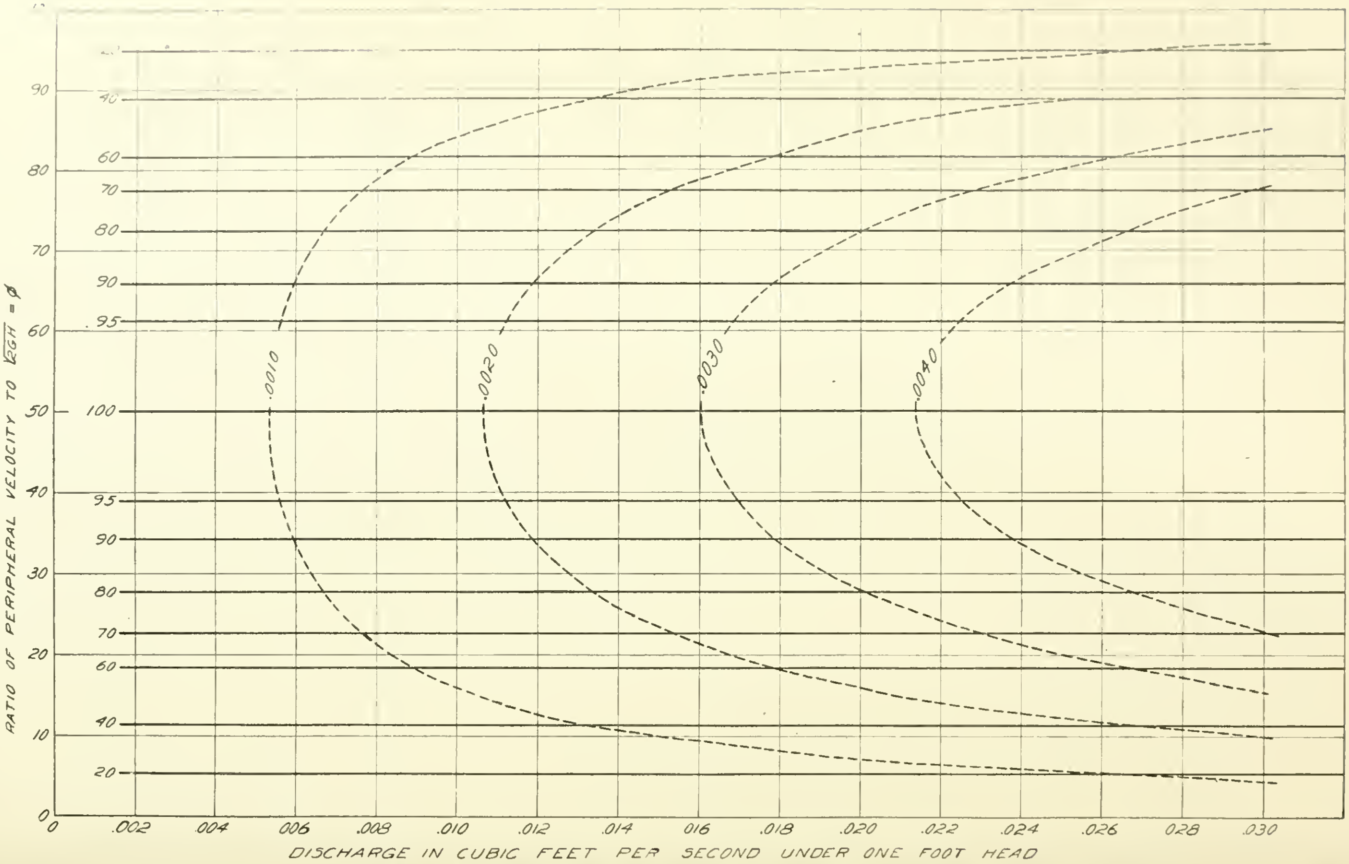


Figure 41.—Theoretical Characteristic Curve of a Twelve Inch Doble Tangential Wheel.

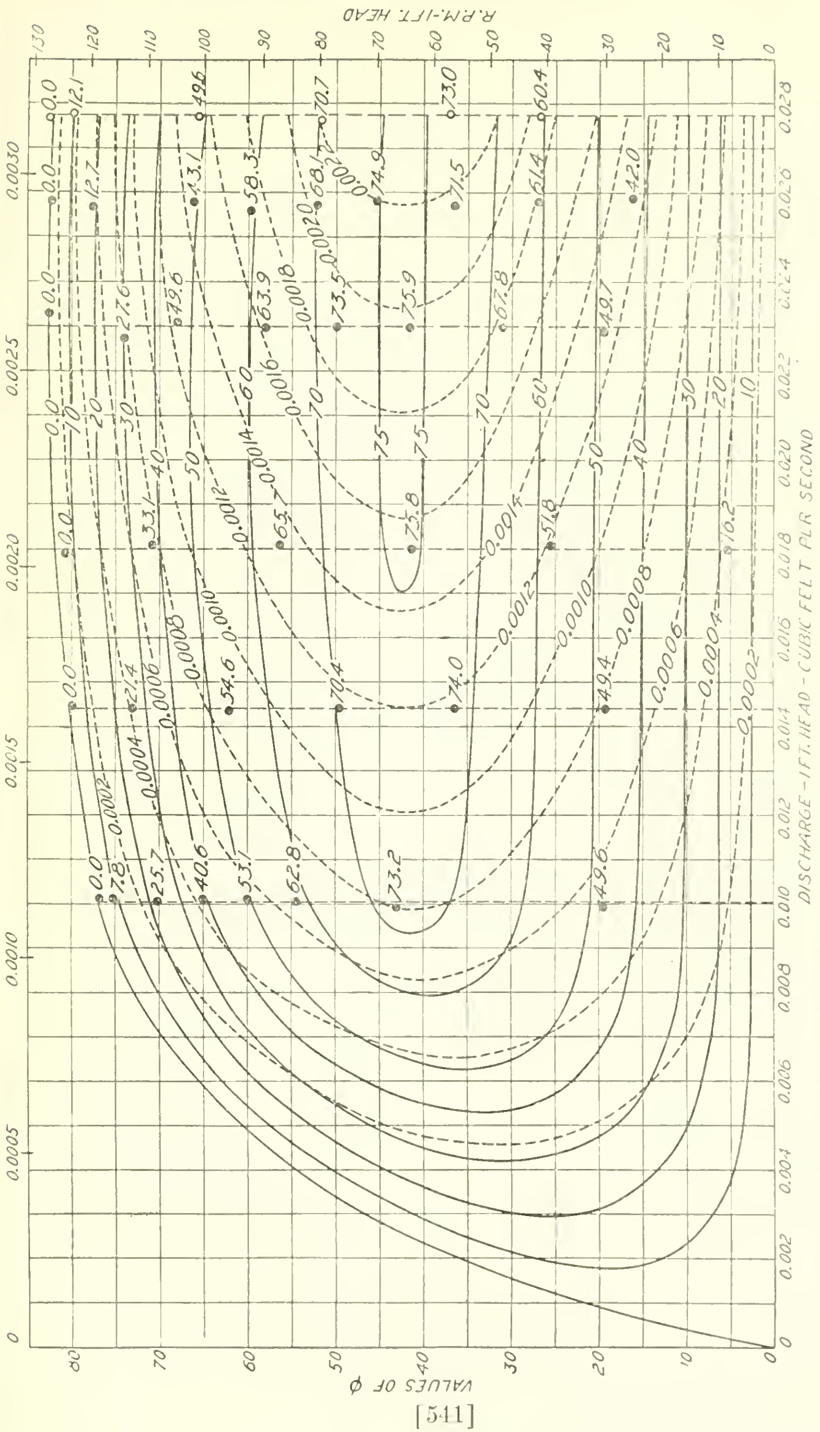


FIGURE 42.—EXPERIMENTAL CHARACTERISTIC CURVE OF TWELVE INCH DOBLE WHEEL BASED ON 60.8 FOOT HEAD.

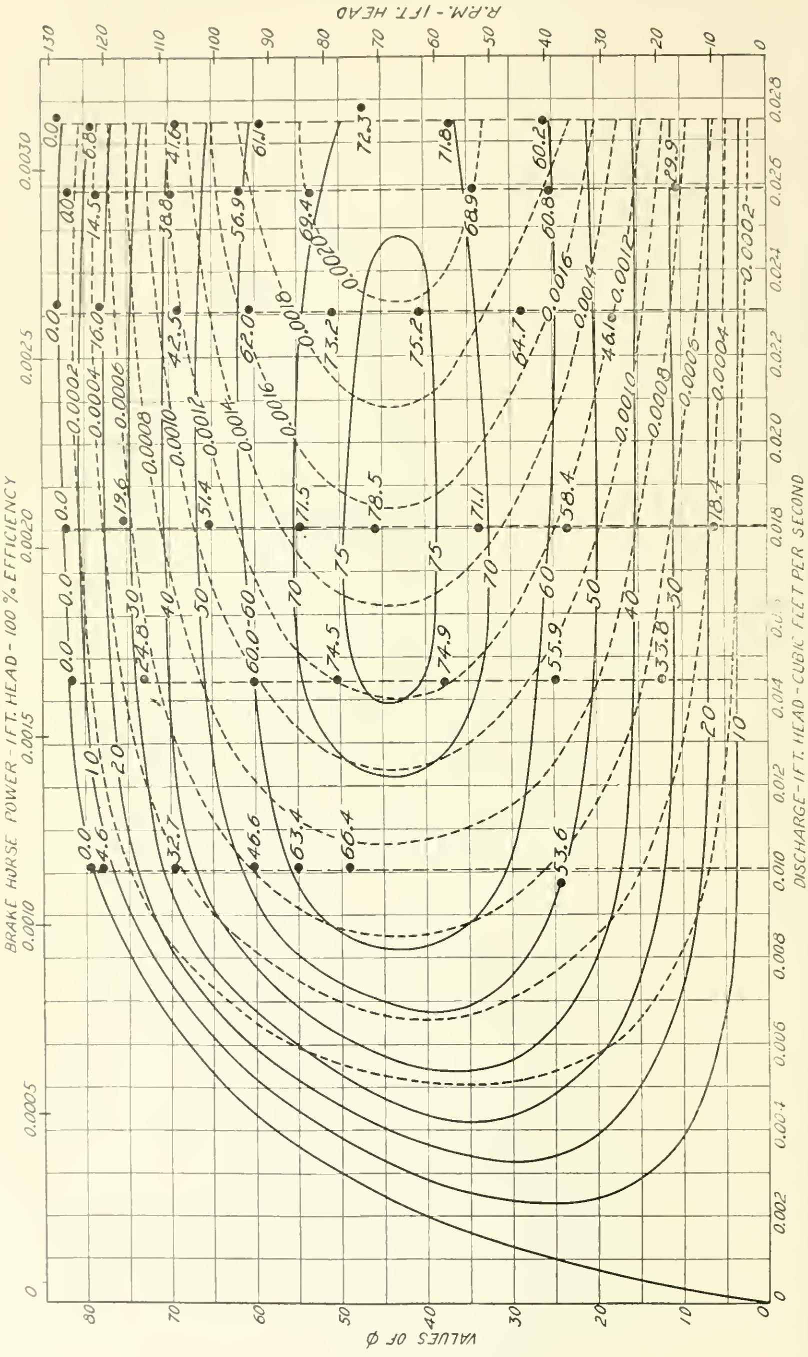


Figure 43.—Experimental Characteristic Curve of Twelve Inch Doble Wheel Based on 108 Foot Head.

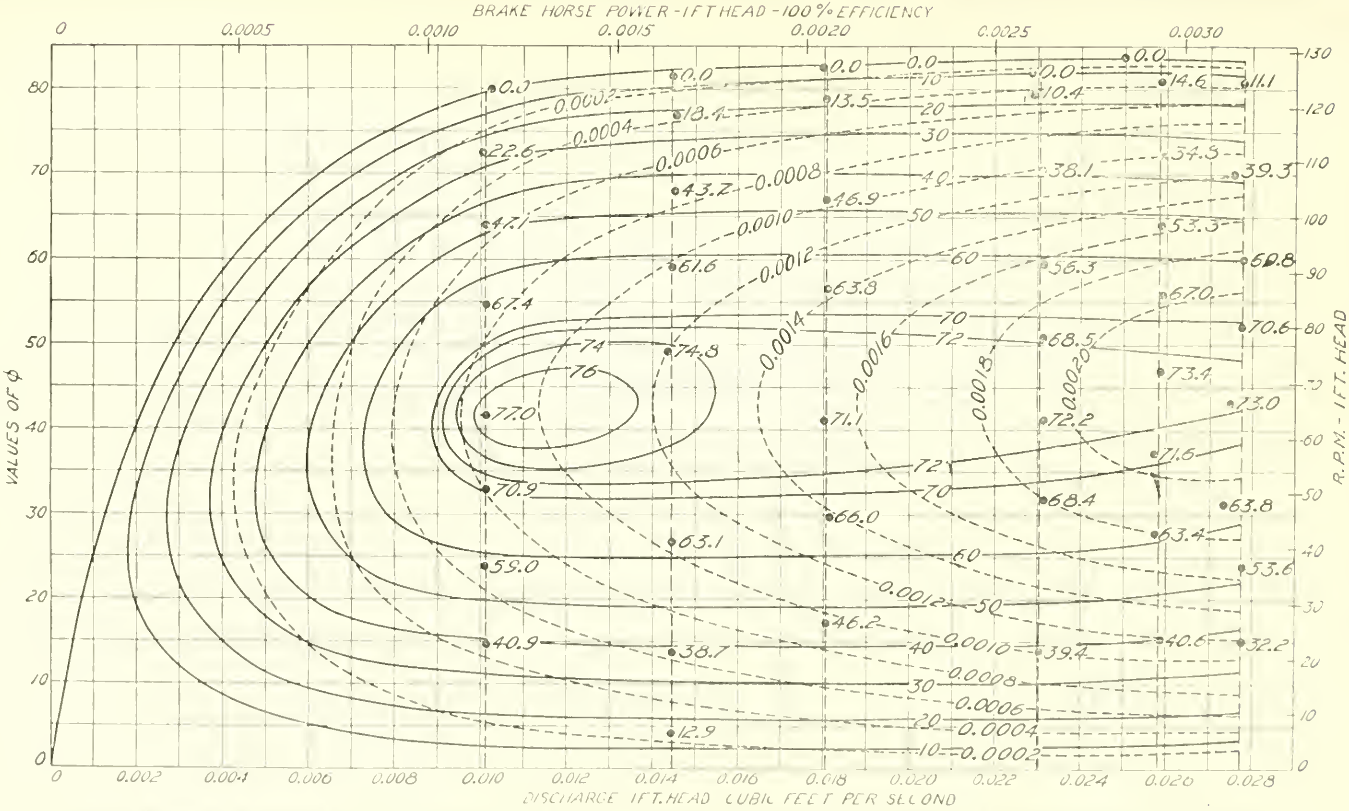


FIGURE 44. —EXPERIMENTAL CHARACTERISTIC CURVE OF TWELVE INCH DOBLE WHEEL BASED ON 161.6 FOOT HEAD.

the general relations of theory to the practical condition are those which would naturally be anticipated. Theoretically, in a frictionless wheel the maximum efficiency is independent of discharge. Practically, with the normal friction and windage of a wheel, a certain discharge is necessary to overcome the friction; hence the curve of zero efficiency must pass obliquely from the line of zero efficiency at maximum q and ϕ to a point at the right of the ordinate $q = o$ to the line $\phi = o$.

It should be noted that, as the efficiency varies with the discharge on account of the bucket efficiency, the area of maximum efficiency moves farther to the left in the characteristic curve, as the head from which the curve is platted increases. This is caused by the fact that the discharge increases with increased head, and the bucket efficiency therefore diminishes.

Practical Analysis from Characteristic Curves.

With due allowance for the variation in efficiency above indicated, it is evident that the characteristic curve furnishes a useful, practical method for the analysis of the action of an experimental wheel under variations in head. Figs. 45, 46 and 47 show analyses of the action of the experimental wheel at 500, 700 and 900 revolutions per minute, based on the data shown in the characteristic curves, Figs. 42, 43 and 44. All calculations are based on the theorems that as long as ϕ remains constant

e_a is constant,
P_a varies with $h^{3}/^{2}$,
q and n vary with $\sqrt{h}$.

The comparatively close agreement of the results derived from the three characteristic curves shows the practical value of the method of analysis. The greatest differences occur between the points on the efficiency curve, in which it will again be noted that as a rule the efficiency decreases with the head, i. e., as the relative discharge of the nozzle increases and the efficiency of the bucket decreases.

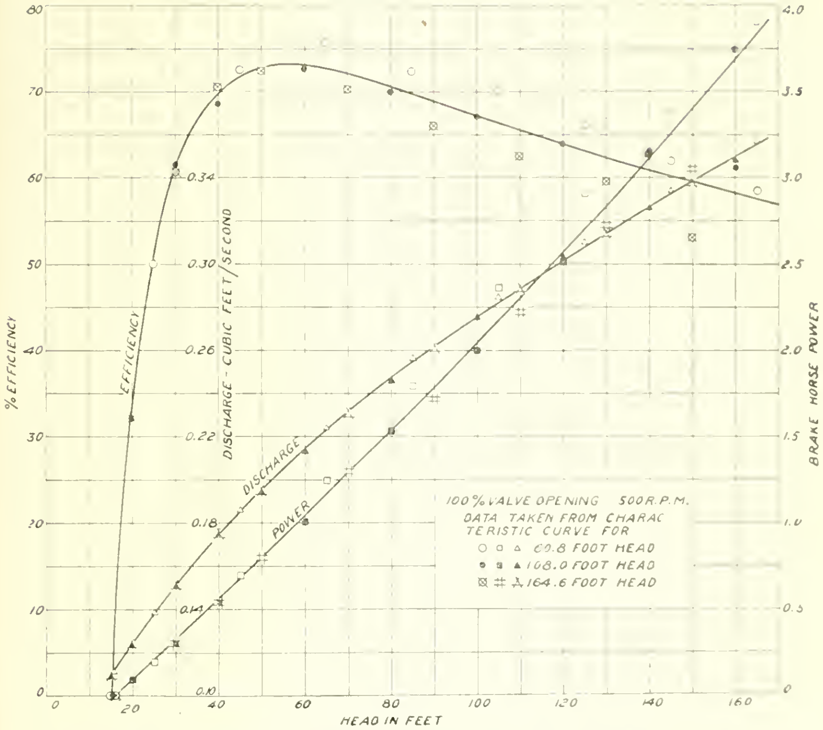


Figure 45.—Relative Efficiency, Power, and Discharge of Doble Wheel With Full Nozzle Opening and at 500 R. P. M. for Various Heads, Based on Characteristic Curves.

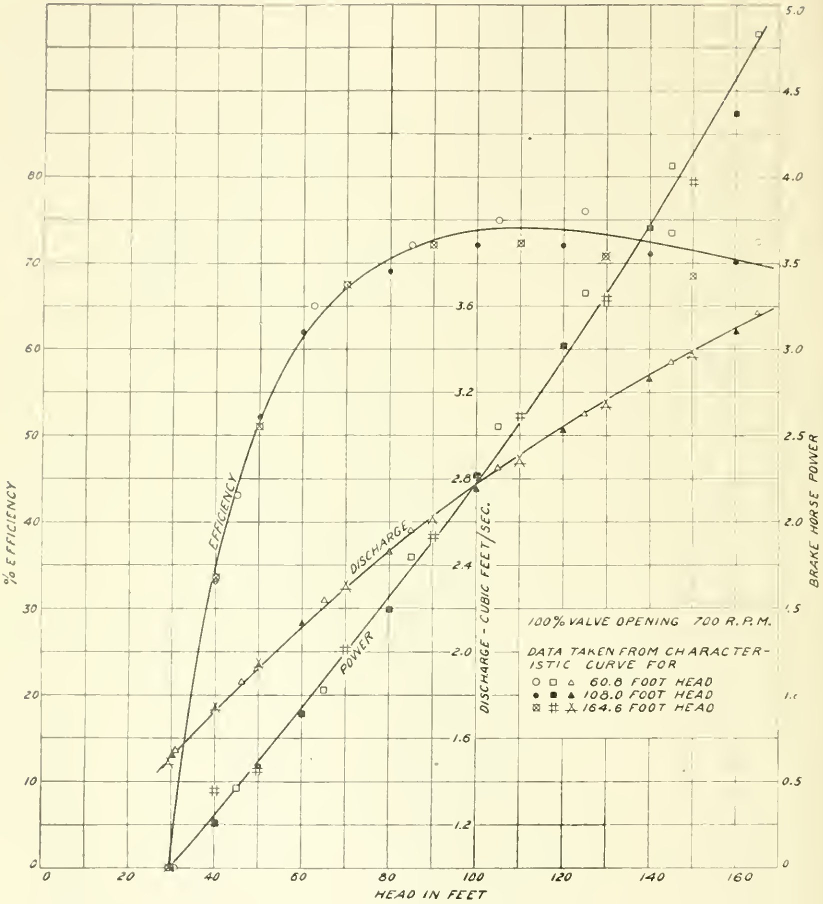


Figure 46.—Relative Efficiencies, Power, and Discharge of Doble Wheel With Full Nozzle Opening and at 700 R. P. M. for Various Heads, Based on Characteristic Curves.

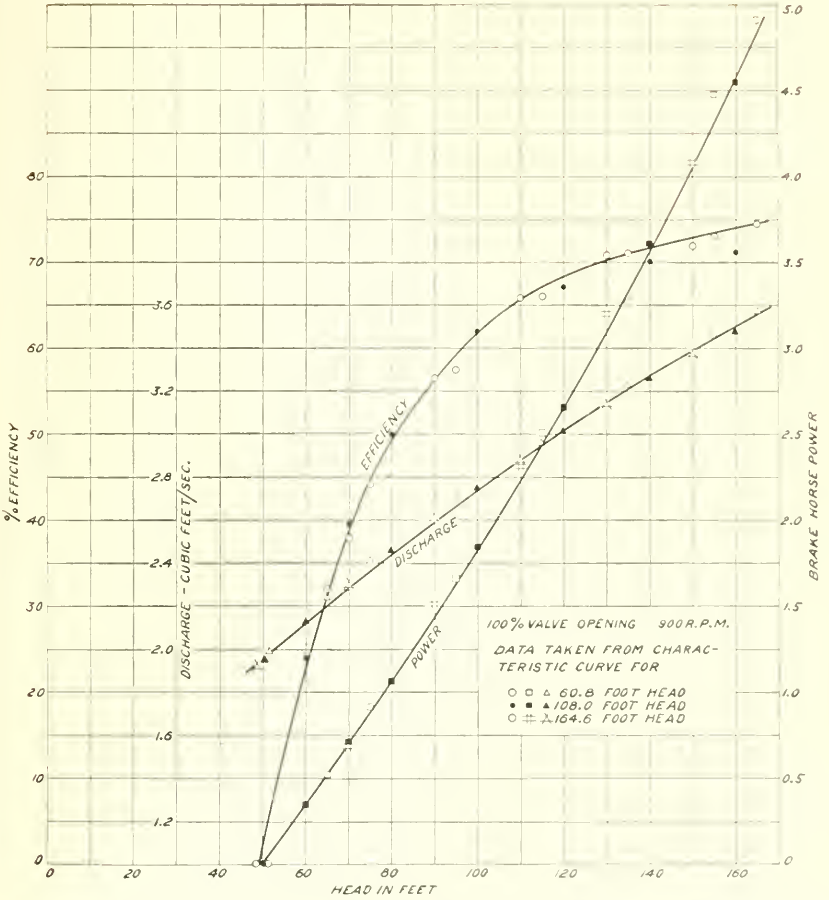


FIGURE 47.—RELATIVE EFFICIENCIES, POWER, AND DISCHARGE OF DOBLE WHEEL WITH FULL NOZZLE OPENING AND AT 900 R. P. M. FOR VARIOUS HEADS, BASED ON CHARACTERISTIC CURVES.

NOMENCLATURE

α = Angle of discharge from bucket. (See Fig. 10.)
c = Coefficient of discharge for an orifice.
D = Diameter of wheel in inches.
e = Efficiency of the bucket.
e_a = Efficiency of the entire wheel.
e_b = Bucket efficiency when stationary.
E' = Energy actually delivered by the wheel.
E_1 = Energy (potential) of water in the fore bay.
E_2 = Energy of water just before entering the nozzle.
E_3 = Energy of the jet.
E_4 = Energy of the jet which can theoretically be recovered by the buckets.
F = Theoretical pressure of a jet against the bucket.
F' = Force to produce a jet.
F_a = Pressure exerted by a jet against a stationary bucket.
g = Accelleration due to gravity.
h = Head.
L = Brake load, in ounces.
L_1 = Brake load, one foot head, in ounces.
l = Length of brake arm.
n = R. P. M. of wheel.
n_1 = R. P. M. under one foot head.
p = Pressure lost by journal friction and windage.
P_a = Power measured by Prony brake.
P_e = Theoretical power of the water used.
q = Discharge of jet in cubic feet per second.
r = Radius of wheel.
r' = Jet pressure on the bucket per (r. p. m.)^2 to overcome windage and journal friction.
v = Velocity of discharge from a jet in feet per second.
v' = Velocity of periphery of wheel.
v_r = Velocity of the jet relative to the bucket.
v_R = Absolute residual velocity with which water leaves bucket.
W = Discharge of jet in pounds per second.
w = Weight of a cubic foot of water = 62.5 pounds.
ϕ = Ratio of peripheral velocity of the wheel to the velocity of the jet.

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APPENDIX.

TABLE A. VALVE OPENING, 36 PER CENT.

Division a. Head, 13.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
126.6	815	0	300
139.4	596	4	300
140.6	316	8	300
140.6	96	10	300
	Division b. Head, 24.9 ft.		
100.4	894	0	300
100.8	771	4	300
97.2	606	8	300
96.6	494	12	300
99.8	323	16	300
101.4	163	20	300
	Division c. Head, 36 ft.		
80.8	926	0	300
80.8	837	4	300
81.2	604	16	300
80.4	346	24	300
81.6	105	32	300
	Division d. Head, 49.3 ft.		
114.2	1538	0	500
112.6	1469	2	500
112.8	1293	10	500
114.2	1059	18	500
119.6	621	32	500
115.8	179	40	500

Division e. Head, 60.8 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
101.6	1553	0	500
101.2	1518	2	500
102.0	1421	7	500
101.4	1312	12	500
101.4	1210	17	500
102.0	1104	22	500
103.4	885	32	500
103.6	428	48	500

Division f. Head, 72.4 ft.

93.0	1554	0	500
92.8	1536	2	500
92.2	1365	12	500
92.8	1193	22	500
92.4	1028	32	500
95.0	833	40	500

Division g. Head, 83.5 ft.

87.0	1549	2	500
121.2	1855	17	700
121.4	1646	27	700
121.8	1441	37	700
121.4	2218	0	700
87.8	804	48	500

Division h. Head, 94.8 ft.

113.4	2243	0	700
113.2	2195	2	700
112.8	2079	8	700
113.0	1851	20	700
113.2	1638	32	700
115.6	1475	40	700
117.2	926	64	700

Division i. Head, 107.8 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
106.6	1387	48	700
106.6	1557	40	700
106.2	1698	32	700
106.4	1962	16	700
106.4	2200	2	700
106.4	2240	0	700
111.0	706	80	700

Division j. Head, 118.2 ft.

116.2	2569	0	800
116.0	2517	2	800
115.6	2406	8	800
116.2	2282	16	800
116.4	2146	24	800
115.6	2010	32	800
116.4	1886	40	800
116.0	1730	48	800
116.4	1578	56	800
116.8	1391	64	800
116.4	1019	80	800
117.0	468	96	800

Division k. Head, 129.5 ft.

110.8	2509	2	800
110.6	2410	8	800
110.0	2279	16	800
110.0	2047	32	800
111.6	1940	40	800
110.8	1775	48	800
111.0	1647	56	800
111.0	1477	64	800
110.8	2559	0	800
111.4	651	104	800

Division l. Head, 141.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
106.2	2571	0	800
106.2	2531	2	800
106.4	2389	12	800
105.6	2226	22	800
106.2	2098	32	800
106.8	1815	52	800
106.0	1661	62	800
106.2	1493	72	800
105.8	1158	88	800

Division m. Head, 152.9 ft.

102.2	2406	12	800
102.0	2137	32	800
102.2	1937	48	800
102.2	1717	64	800
102.4	1481	80	800
102.4	1201	96	800
102.2	901	112	800
103.2	586	124	800
102.4	2574	0	800

Division n. Head, 164.4 ft.

133.6	3508	0	1100
99.2	2361	16	800
98.4	2065	40	800
98.4	1762	64	800
98.4	1343	96	800
98.4	1061	112	800
98.8	771	128	800
98.6	475	144	800

TABLE B. VALVE OPENING, 52 PER CENT.

Division a. Head, 13.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
151.8	1016	0	500
152.4	653	8	500
151.8	166	16	500
Division b. Head, 24.9 ft.			
114.6	751	12	500
112.2	634	16	500
112.2	443	24	500
Division c. Head, 36.4 ft.			
92.2	1110	0	500
93.4	827	16	500
93.0	675	24	500
92.4	523	32	500
91.8	338	40	500
Division d. Head, 49.3 ft.			
79.0	907	16	500
111.8	1131	24	700
111.2	829	40	700
110.8	638	48	700
111.0	382	56	700
111.2	1571	0	700
Division e. Head, 60.8 ft.			
99.2	1580	0	700
99.6	1451	8	700
100.0	1236	24	700
99.6	981	40	700
99.8	723	56	700
99.8	378	72	700

Division f. Head, 72.4 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
91.6	1486	8	700
90.8	1198	32	700
91.2	980	48	700
91.4	769	64	700
91.6	482	80	700
91.6	146	96	700
91.2	1592	0	700

Division g. Head, 83.6 ft.

84.6	1502	8	700
96.8	1324	40	800
97.0	1009	64	800
97.0	622	88	800
97.0	194	112	800
97.0	1822	0	800

Division h. Head, 94.9 ft.

101.8	2064	0	900
101.4	1842	16	900
101.6	1460	48	900
101.6	1147	72	900
101.6	766	96	900
101.8	375	120	900

Division i. Head, 107.9 ft.

106.2	2083	16	1000
106.8	1719	48	1000
106.6	1422	72	1000
107.0	1071	96	1000
106.6	640	120	1000
106.8	351	136	1000
106.2	2299	0	1000

	Division j.	Head, 118.3 ft.	
Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
101.4	2299	0	1000
101.6	2119	16	1000
102.0	1794	48	1000
100.8	1502	72	1000
101.0	1232	96	1000
121.4	1022	120	1000
101.4	492	144	1000
	Division k.	Head, 129.6 ft.	
96.4	2099	16	1000
96.4	1877	40	1000
96.2	1636	64	1000
97.0	1416	88	1000
96.8	1134	112	1000
97.8	787	136	1000
96.6	452	160	1000
97.6	99	184	1000
97.0	2280	0	1000
	Division l.	Head, 141.4 ft.	
92.6	2290	0	1000
92.6	2127	16	1000
93.0	1921	40	1000
92.8	1655	72	1000
92.4	1318	104	1000
92.6	1007	128	1000
92.8	726	152	1000
93.0	413	176	1000
93.0	171	192	1000
	Division m.	Head, 153.0 ft.	
89.4	2154	16	1000
88.8	1881	48	1000
89.0	1344	112	1000
89.2	958	144	1000
88.6	632	176	1000
89.4	230	208	1000
89.4	2312	0	1000

Division n. Head, 164.5 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
85.6	2153	16	1000
103.0	2293	48	1200
103.4	1999	80	1200
104.0	1671	112	1200
103.4	902	176	1200
103.2	465	208	1200
103.6	140	232	1200
103.2	2759	0	1200

TABLE C. VALVE OPENING, 66 PER CENT.

Division a. Head, 13.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
122.2	860	0	500
119.8	716	5	500
120.6	485	12	500
121.2	139	20	500
120.0	334	16	500

Division b. Head, 24.9 ft.

88.6	741	8	500
89.8	465	24	500
89.2	281	32	500
89.6	69	40	500
90.2	886	0	500

Division c. Head, 36.4 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
72.8	802	8	500
116.8	992	24	800
116.8	846	32	800
117.0	675	40	800
116.8	480	48	800
116.6	263	56	800
117.0	1436	0	800

Division d. Head, 49.3 ft.

101.0	1457	0	800
100.2	1341	8	800
101.8	1139	24	800
101.8	898	40	800
101.2	665	56	800
101.4	333	72	800
101.2	170	80	800

Division e. Head, 60.8 ft.

90.8	1280	16	800
90.8	1018	40	800
91.2	733	64	800
90.8	369	87	800
91.2	97	103	800
91.6	1473	0	800

Division f. Head, 72.4 ft.

83.6	1308	16	800
104.2	1366	40	1000
104.2	1065	64	1000
104.2	755	88	1000
124.8	415	112	1200
103.6	1838	0	1000

Division g. Head, 83.7 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
96.8	1852	0	1000
96.8	1680	16	1000
125.4	1876	40	1300
96.8	941	88	1000
96.2	1186	64	1000
96.8	594	112	1000
97.2	228	136	1000

Division h. Head, 95.0 ft.

90.6	1705	16	1000
91.0	1516	40	1000
90.6	1274	64	1000
91.0	1063	88	1000
90.6	776	112	1000
91.0	503	136	1000
90.6	176	160	1000
91.0	1855	0	1000

Division i. Head, 108.0 ft.

85.4	1862	0	1000
101.2	2021	16	1200
102.0	1766	48	1200
102.2	1477	80	1200
102.8	1247	104	1200
102.6	918	128	1200
102.8	632	152	1200
102.8	165	184	1200

Division j. Head, 118.4 ft.

97.0	2223	0	1200
97.8	2104	16	1200
97.8	1873	40	1200
97.8	1605	72	1200
97.8	1335	104	1200
97.8	953	136	1200
97.8	602	168	1200
97.8	176	200	1200

Division k. Head, 129.7 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
93.8	2244	0	1200
92.8	2095	16	1200
93.8	1843	48	1200
93.2	1581	80	1200
93.0	1332	112	1200
93.6	1036	144	1200
93.2	696	176	1200
93.6	324	208	1200

Division l. Head, 141.5 ft.

88.4	2104	16	1200
89.4	1876	48	1200
89.0	1642	80	1200
89.2	1408	112	1200
89.6	1193	144	1200
89.6	808	175	1200
90.0	494	208	1200
89.6	127	240	1200
89.4	2237	0	1200
89.4	1176	144	1200
89.4	1183	144	1200

Division m. Head, 153.1 ft.

85.8	2242	0	1200
85.8	2119	16	1200
85.8	1845	56	1200
85.8	1577	96	1200
85.8	1308	136	1200
85.8	929	176	1200
85.8	572	216	1200
86.0	354	240	1200
86.0	206	255	1200

Division n. Head, 164.6 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
82.2	2126	16	1200
89.8	1976	64	1300
89.6	1663	112	1300
90.0	1297	160	1300
89.2	864	208	1300
89.8	505	248	1300
69.4	1879	0	1000

Division o. Head, 177.4 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
85.8	2305	16	1300
85.8	1996	64	1300
85.8	1703	112	1300
86.4	1410	160	1300
86.4	974	208	1300
86.2	620	256	1300
86.4	409	280	1300
86.4	2430	0	1300

TABLE D. VALVE OPENING, 84 PER CENT.

Division a. Head, 13.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
94.2	509	8	500
94.6	377	16	500
94.6	165	24	500
93.0	44	30	500
94.0	688	0	500

Division b. Head, 24.9 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
84.4	740	8	600
112.2	706	24	800
113.0	569	32	800
113.6	351	40	800
113.6	120	48	800
112.2	1127	0	800

Division c. Head, 36.5 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
90.6	1132	0	800
92.2	155	72	800
91.8	950	16	800
92.0	855	24	800
91.6	756	32	800
92.0	678	40	800
91.8	576	48	800
92.6	427	56	800
91.8	288	64	800

Division d. Head, 49.4 ft.

100.0	1448	0	800
100.6	1260	16	800
102.0	1010	40	800
101.2	727	64	800
102.0	354	88	800
99.8	202	96	800

Division e. Head, 60.9 ft.

88.2	1451	0	1000
72.0	1062	16	800
71.0	931	32	800
71.4	832	48	800
71.4	710	64	800
71.2	589	80	800
71.2	438	96	800
71.6	277	112	800

Division f. Head, 72.5 ft.

97.2	1749	0	1200
96.6	1600	16	1200
97.0	1384	40	1200
97.4	1174	64	1200
97.2	961	88	1200
97.8	678	112	1200
97.2	380	136	1200

Division g. Head, 83.8 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
90.6	1752	0	1200
90.2	1615	16	1200
90.2	1376	48	1200
90.2	1182	72	1200
90.6	1010	96	1200
90.6	778	120	1200
90.6	445	152	1200

Division h. Head, 95.1 ft.

84.6	1752	0	1200
84.0	1620	16	1200
85.2	1425	48	1200
84.2	1208	80	1200
85.2	991	112	1200
120.0	1012	144	1700
84.6	430	176	1200

Division i. Head, 108.1 ft.

79.2	1748	0	1200
79.4	1650	16	1200
79.8	1463	48	1200
79.8	1280	80	1200
80.0	1077	112	1200
80.0	861	144	1200
80.0	607	176	1200
80.6	392	200	1200

Division j. Head, 118.5 ft.

75.8	1759	0	1200
76.2	1670	16	1200
76.2	1444	56	1200
76.2	1268	88	1200
76.2	1097	120	1200
76.2	907	152	1200
76.0	670	184	1200
76.2	323	232	1200

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
	Division k. Head, 129.9 ft.		
72.0	1741	0	1200
73.0	1685	16	1200
73.0	1469	56	1200
73.2	1270	96	1200
73.0	1074	136	1200
73.2	886	168	1200
73.4	677	200	1200
73.0	471	232	1200
	Division l. Head, 141.7 ft.		
70.2	1777	0	1200
75.8	1834	16	1300
74.8	1565	64	1300
75.4	1385	104	1300
76.4	1190	144	1300
75.8	1012	176	1300
76.2	798	208	1300
75.8	612	240	1300
	Division m. Head, 153.3 ft.		
83.6	2202	0	1500
83.4	2111	16	1500
83.6	1849	64	1500
83.6	1599	112	1500
83.0	1335	160	1500
83.6	1032	208	1500
83.6	741	256	1500
83.8	342	304	1500
	Division n. Head, 164.9 ft.		
81.8	2196	0	1500
81.6	2120	16	1500
81.0	1872	64	1500
80.8	1634	112	1500
80.8	1395	160	1500
80.8	1128	208	1500
80.8	840	256	1500
81.2	368	320	1500

Division o. Head, 177.6 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
78.2	2206	0	1500
77.8	2131	16	1500
78.2	1990	64	1500
78.4	1691	112	1500
78.0	1449	160	1500
77.8	1199	208	1500
78.0	906	256	1500
77.8	645	304	1500
77.4	401	336	1500

TABLE E. VALVE OPENING, 91 PER CENT.

Division a. Head, 13.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
83.4	627	0	500
133.8	756	8	800
135.6	553	16	800
85.2	169	24	500
85.2	84	28	500
Division b. Head, 24.9 ft.			
63.2	644	0	500
63.4	551	8	500
101.4	777	16	800
101.8	653	24	800
101.4	534	32	800
101.8	413	40	800
101.8	222	48	800
99.4	107	56	800

Division c. Head, 36.5 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
81.8	1030	0	800
82.2	947	8	800
82.0	788	24	800
82.8	642	40	800
82.8	477	56	800
82.0	240	72	800
	Division d. Head, 49.4 ft.		
88.8	1300	0	1000
88.8	993	32	1000
89.0	851	48	1000
89.4	704	64	1000
88.8	515	80	1000
	Division e. Head, 61.0 ft.		
79.4	1305	0	1000
79.8	1234	8	1000
79.4	1056	32	1000
80.0	949	48	1000
79.6	826	64	1000
79.4	716	80	1000
79.6	578	96	1000
79.4	425	112	1000
79.2	255	128	1000
	Division f. Head, 72.6 ft.		
72.2	1303	0	1000
73.0	1209	16	1000
73.0	1053	40	1000
73.0	911	64	1000
73.0	773	88	1000
73.2	727	96	1000
72.8	598	112	1000
72.8	400	136	1000
73.0	182	160	1000

Division g. Head, 83.8 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
81.4	1575	0	1200
81.2	1470	16	1200
81.4	1268	48	1200
81.0	1070	80	1200
81.2	916	104	1200
81.4	732	128	1200
81.4	535	152	1200
81.4	299	176	1200

Division h. Head, 95.2 ft.

88.6	1836	0	1400
63.2	1233	16	1000
75.8	1346	40	1200
75.8	1224	64	1200
76.0	1080	88	1200
76.2	949	112	1200
75.8	807	136	1200
76.0	637	160	1200
76.0	469	184	1200
75.8	277	208	1200

Division i. Head, 108.2 ft.

71.4	1502	16	1200
83.4	1561	48	1400
83.2	1372	80	1400
83.4	1193	142	1400
83.2	756	176	1400
83.4	564	208	1400
83.2	231	240	1400
89.0	1961	0	1500

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
Division j. Head, 118.7 ft.			
84.6	1601	64	1500
85.0	1332	112	1500
85.0	1108	152	1500
84.8	826	192	1500
85.2	558	232	1500
84.8	334	256	1500
85.0	1967	0	1500
Division k. Head, 130.0 ft.			
81.6	1974	0	1500
80.8	1882	16	1500
81.4	1553	80	1500
80.8	1307	128	1500
81.6	1050	176	1500
81.4	756	224	1500
81.4	407	272	1500
Division l. Head, 141.8 ft.			
77.8	1980	0	1500
78.4	1906	16	1500
77.8	1652	64	1500
77.8	1445	112	1500
78.2	1220	160	1500
78.0	947	208	1500
77.8	687	256	1500
78.4	354	304	1500
Division m. Head, 153.4 ft.			
75.0	1917	16	1500
74.8	1681	64	1500
74.6	1479	112	1500
74.8	1277	160	1500
74.8	1048	208	1500
75.0	797	256	1500
74.0	524	304	1500
75.0	1979	0	1500

Division n. Head, 165.0 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
74.8	2055	0	1500
72.2	1917	16	1500
72.2	1711	64	1500
72.2	1519	112	1500
72.0	1317	160	1500
72.2	1112	208	1500
72.6	882	256	1500
72.6	657	304	1500
72.2	363	352	1500

TABLE F. VALVE OPENING, 100 PER CENT.

Division a. Head, 13.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
125.4	929	0	800
78.8	470	8	500
79.2	359	16	500
78.8	238	24	500
126.8	222	28	800

Division b. Head, 25.0 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
93.6	950	0	800
93.6	849	8	800
93.2	651	24	800
93.6	558	32	800
93.2	455	40	800
94.0	148	72	800

Division c. Head, 36.6 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
76.4	965	0	800
95.6	1125	8	1000
95.8	877	32	1000
95.4	616	56	1000
95.6	390	72	1000
95.6	186	84	1000

Division d. Head, 49.4 ft.

66.0	971	0	800
82.4	1155	8	1000
82.2	905	40	1000
82.0	833	48	1000
82.4	650	72	1000
82.0	398	96	1000
82.6	221	112	1000

Division e. Head, 61.0 ft.

74.0	1217	0	1000
95.8	1525	8	1300
96.0	1254	40	1300
96.4	990	72	1300
95.8	709	104	1300
96.0	509	120	1300

Division f. Head, 72.6 ft.

67.8	1216	0	1000
88.8	1478	8	1300
88.4	1249	48	1300
88.2	1090	72	1300
88.4	923	96	1300
88.0	731	120	1300
88.6	510	144	1300
88.6	255	164	1300

Division g. Head, 83.9 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
75.4	1467	0	1200
82.6	1504	8	1300
82.6	1302	48	1300
82.2	1099	80	1300
82.6	920	112	1300
82.6	676	144	1300

Division h. Head, 95.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
70.4	1468	0	1200
77.8	1525	8	1300
77.4	1340	48	1300
77.4	1174	80	1300
77.2	998	112	1300
77.6	815	144	1300
77.4	606	176	1300

Division i. Head, 108.3 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
77.8	1715	0	1400
84.0	1768	8	1500
83.8	1540	56	1500
83.8	1317	96	1500
83.4	1104	136	1500
84.0	844	176	1500
83.8	577	216	1500

Division j. Head, 118.7 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
74.4	1723	0	1400
80.0	1781	8	1500
80.0	1527	64	1500
79.8	1325	104	1500
80.0	1130	144	1500
80.2	893	184	1500
79.8	668	224	1500
80.0	382	264	1500

Division k. Head, 130.4 ft.

Time Seconds	Total Revolutions	Corrected Brake Weight oz.	Discharge in Pounds
70.6	1713	0	1400
76.2	1780	16	1500
76.8	1548	64	1500
76.8	1320	112	1500
76.2	1102	160	1500
76.6	832	208	1500
76.2	558	256	1500
76.2	392	288	1500

Division l. Head. 141.9 ft.

73.2	1859	0	1500
73.4	1796	16	1500
73.4	1578	64	1500
73.4	1380	112	1500
73.4	1161	160	1500
73.0	936	208	1500
73.2	718	256	1500
73.2	418	314	1500

Division m. Head. 153.5 ft.

70.0	1793	16	1500
69.8	1527	80	1500
70.0	1346	128	1500
70.0	1161	176	1500
70.0	944	224	1500
70.0	735	272	1500
70.0	479	320	1500

Division n. Head. 165.1 ft.

67.2	1783	16	1500
67.6	1553	80	1500
67.8	1331	144	1500
67.8	1160	192	1500
68.0	961	240	1500
82.0	849	288	1800
67.8	532	336	1500
67.8	334	368	1500

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